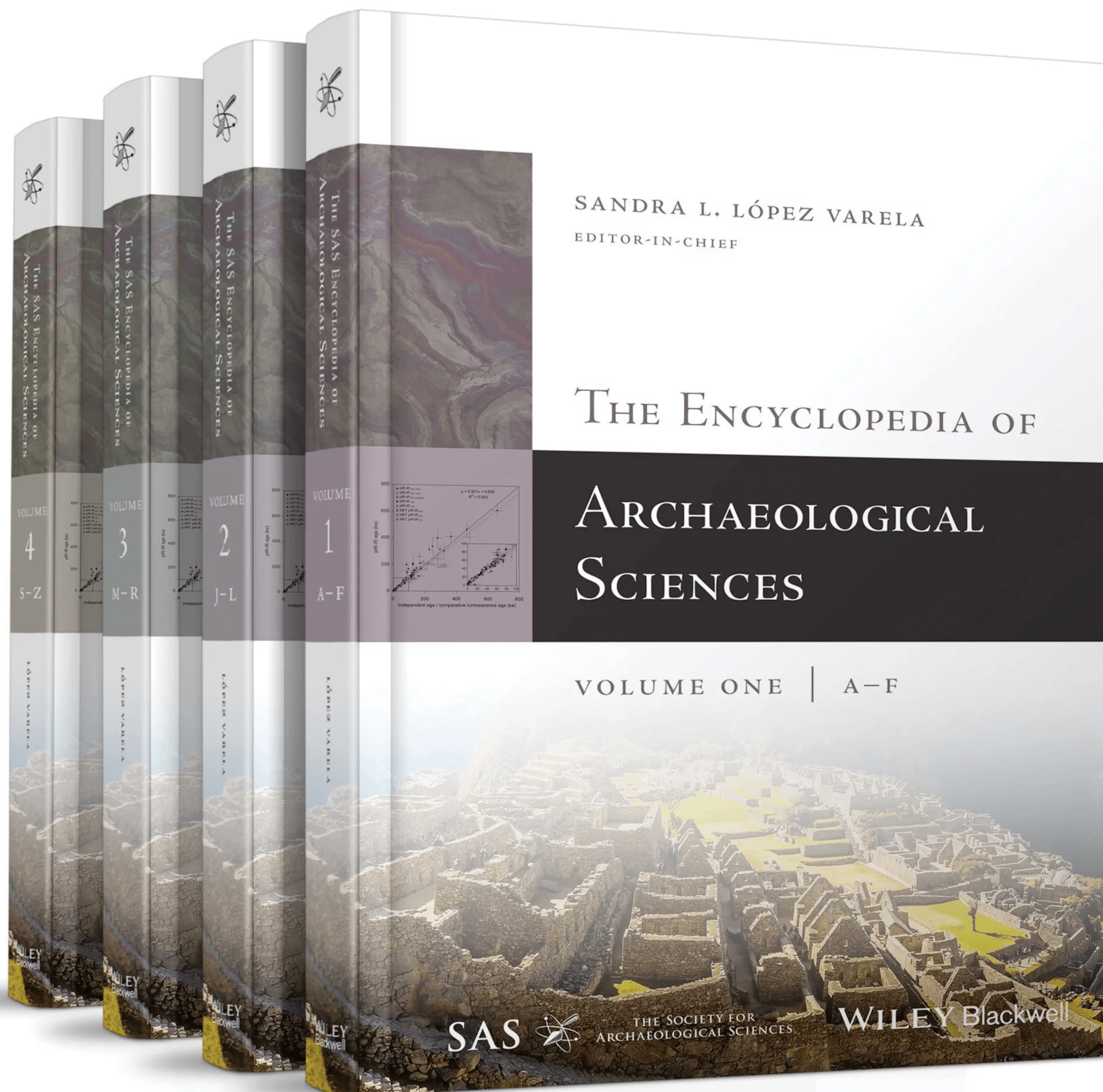




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Anemia

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Anemia is defined as “a condition in which the number of red blood cells (and consequently their oxygen carrying capacity) is insufficient to meet the body’s physiologic needs” (WHO 2011). The main congenital and/or acquired anemias discussed here include the hypochromic (and often microcytic), macrocytic, hemolytic, and aplastic anemias. Only a select range of common forms of these conditions are discussed, followed by a brief review of what are arguably skeletal signatures of some of the anemias. Note that the term erythrocyte or erythroid refers to red blood cells (RBC), while erythropoiesis describes the production of RBCs (in distinction to hemopoiesis, which refers to the production of all blood cells), and erythroid hyperplasia describes the excessive production of such cells or their precursors.

Hypochromic anemias

Iron deficiency anemia (IDA) is initially normocytic (normal cell size) and normochromic (normal cell color) with hypoproliferative bone marrow, but develops into a microcytic (small cell size), hypochromic (pale color) form (severe IDA) if untreated. Normal iron requirements differ by age and sex, with adult males requiring 0.5–1.0 mg/day compared to menstruating or pregnant females who require 1.0–3.0 mg/day or females aged 12–15 years who need 1.6–2.6 mg/day. Iron deficiency can be due to a range of causes including blood loss (e.g., parasitic infections, stomach ulcers, menarche, and trauma), physiological demands (e.g., prematurity, childhood growth, and pregnancy), malabsorption, and poor diet (Hoffbrand and Moss 2016). Erythroid hyperplasia (overproduction of RBC precursors) associated with

microcytic (small RBC) anemia is most commonly caused by iron deficiency. It is important to understand that in early to mild forms of IDA, erythroid hypoproliferation (underproduction) occurs, while in severe IDA, erythroid hyperplasia develops. Indeed, erythroid hyperplasia is seen in anemias involving RBC loss and destruction, and in conditions that include ineffective erythropoiesis. It is worth noting that two quite distinct anemic conditions (e.g., iron overloading diseases such as thalassemia and iron deficient conditions) are associated with suppression of hepcidin (the chief iron regulatory hormone) and concomitant increases in erythropoiesis. Hepcidin levels appear to be controlled by erythropoietic activity and not by iron levels in and of themselves. Similarly, soluble transferrin (a protein used in iron transport in the blood) levels in plasma are a measure of erythropoietic activity. Anemias associated with ineffective erythropoiesis (including IDA) display elevated levels of soluble transferrin receptors.

Anemia of chronic disorders (ACD) is associated with underlying chronic infectious (e.g., tuberculosis, osteomyelitis) and non-infectious (e.g., rheumatoid arthritis, sarcoidosis) diseases. ACD will generally only resolve with resolution of the underlying disease, and can be exacerbated by other conditions (e.g., iron, vitamin B₁₂, or folate deficiency). Factors contributing to the pathogenesis of ACD include a reduced level of iron recycling (during RBC turnover), due to increased serum hepcidin levels (in distinction to IDA), reduced RBC longevity, and a poor erythropoietin (EPO, a hormone controlling erythropoiesis) response to anemia. Note that erythroid hyperplasia is not seen in ACD (Hoffbrand and Moss 2016).

Other hypochromic anemias include sideroblastic anemia that results from a failure in heme (an iron compound associated with the transport of oxygen in RBCs) synthesis and can be associated with erythroid hyperplasia and ineffective erythropoiesis. Lead poisoning can lead to anemia, both hypochromic or hemolytic. Finally, iron refractory iron deficiency anemia (IRIDA)

is a relatively rare microcytic, hypochromic (with normal to elevated hepcidin levels) hereditary recessive anemia.

Macrocytic anemias

Megaloblastic anemias are characterized by hypercellular bone marrow and ineffective erythropoiesis (Hoffbrand 2015), and symptoms can include jaundice, glossitis (inflammation of the tongue), and stomatitis (inflammation of the mouth) (Hoffbrand and Moss 2016). These anemias are most commonly caused by vitamin B₁₂ or folate deficiencies that lead to defective DNA synthesis. B₁₂ is found in foods of animal origin and is not present in fruits or vegetables. B₁₂ deficiency is usually related to malabsorption, for which there are numerous causes, including fish tapeworm infections and the intestinal disease tropical sprue. Inadequate dietary intake also occurs, particularly among vegetarians who do not consume any animal products or individuals with very poor diets. Folate (pteroglutamic) acid is found in a range of foods, particularly vegetables and legumes. Folate and B₁₂ deficiencies can cause infertility, while folate deficiency in pregnant women is associated with elevated risks of neural tube defects in their children, while B₁₂ deficiency is associated with various neuropathies (Hoffbrand 2015).

Nonmegaloblastic macrocytic anemias have various causes, from liver disease and aplastic anemia through to pregnancy and smoking (Hoffbrand and Moss 2016).

Hemolytic anemias

Hemolytic anemias (HAs) are caused by an increased rate of RBC destruction (hemolysis) and there are both hereditary and acquired forms of the condition (Luzzatto 2015). Among the *hereditary forms*, severe congenital HA can lead to skeletal changes mediated by bone marrow activity. The two key categories of hereditary HA include those associated with membrane defects and those with defective red cell metabolism.

Membrane defects, caused by various mutations to the membrane proteins of RBCs, include hereditary spherocytosis (HS) and hereditary

elliptocytosis (HE). HS is common in northern Europeans and has autosomal dominant inheritance with variable expression that can manifest from infancy through to old age. It has a frequency of approximately 1 in 5,000. HE has similar clinical features to HS as well as a similar frequency. One form of HE, Southeast Asian ovalocytosis (where the RBCs take on an oval shape), has a frequency of 7 percent, thought to be due to a level of malarial protection afforded to the victim (Hoffbrand and Moss 2016; Luzzatto 2015).

Defective red cell metabolism includes a number of conditions, with glucose-6-phosphate dehydrogenase (G6PD) deficiency being the most important. Hundreds of variants occur and globally 400 million people are G6PD deficient. It is sex-linked (carried by females), with female heterozygotes enjoying falciparum (mosquito parasite) malaria resistance. G6PD deficiency is usually asymptomatic unless an individual is under oxidative stress (suffering from an overabundance of free radicals), which can be caused by a range of drugs, fava beans, or infections (Hoffbrand and Moss 2016; Luzzatto 2015).

Hereditary disorders of hemoglobin synthesis are associated with abnormal or reduced globin (protein chains) synthesis and they are the most common genetic defects globally, evolutionarily selected for due to their ability to protect the organism (or victim) from malarial infections.

Thalassemias, caused by poor globin (α or β chain) synthesis, are frequently seen in subtropical (β form, e.g., Mediterranean) and tropical (α form, e.g., sub-Saharan Africa, Southeast Asia, Middle East, India) regions. β thalassemia ranges from asymptomatic (carrier state) through to intermedia and major forms of the disease. β thalassemia major is transfusion dependent, that is, it causes death within the first or second decades in societies without access to modern medical treatment. It includes symptoms such as severe anemia, spleen and liver enlargement, bone expansion (marrow hyperplasia, skull bossing, hair on end X-rays of diploic bone), osteoporosis, infections, and liver disease. Thalassemia intermedia includes over 200 forms (based on genetic deletions) and can range from limited symptoms through to thalassemia major-type symptoms including, but not limited to, extramedullary erythropoiesis, gall stones, osteoporosis, and bone deformity (Hoffbrand and Moss 2016).

Sickle cell anemia is caused by inheritance of the sickle β -globin gene, with the resulting sickled RBCs causing vessel blockages and localized organ tissue death (i.e., infarcts). Up to 30 percent of Africans have the carrier state, which provides protection from malaria. In its homozygous form, symptoms range from mild to extreme (including severe hemolytic anemia and crises), where crises can include: (1) bone infarcts (especially shoulders, hips, vertebrae, hands, and feet); (2) organ infarcts (e.g., acute sickle chest syndrome, the most common form of death in adults and children); (3) aplastic anemia; (4) hemolytic crises; and (5) lower leg ulcers. Sickle cell can combine with other hemoglobin disorders such as thalassemia (Hoffbrand and Moss 2016).

Aplastic anemias

Aplastic (hypoplastic) anemia is essentially pancytopenia (reduction in all blood cell lines) due to bone marrow hypoplasia and includes primary and secondary (associated with drugs, chemicals, viruses, and transfusions) forms. A primary, congenital, example is *Fanconi's anemia*, often causing skeletal defects and growth retardation, including microcephaly and radius/thumb aplasia. The most common form of aplastic anemia is *idiopathic acquired aplastic anemia*, where an autoimmune response affects hemopoietic (blood cell forming) tissue (Hoffbrand and Moss 2016).

Congenital dyserythropoietic anemias (CDAs) are defined by ineffective erythropoiesis and erythroblast multinuclearity. CDAs are also refractory anemias (i.e., they can only be treated with blood transfusions and are not associated with any other primary disease process) and can cause expansion of the bone marrow (Hoffbrand and Moss 2016).

Skeletal signatures of anemia

In theory, any form of anemia that is associated with a period of erythroid hyperplasia and/or ineffective erythropoiesis has the potential to cause bone marrow expansion, which may manifest skeletally as an expanded medullary space and cortical bone thinning. It is worth noting

that about 25 percent of all active marrow in infants is concentrated in the cranium and all infant bones display 100 percent marrow cellularity, as compared to ca. 7 percent of total active marrow occurring in adult crania (Cristy 1981). As such, children should presumably be at a much greater risk, in comparison to adults, of cranio-facial skeletal changes when subject to a range of acquired and congenital anemias.

While skeletal changes associated with some hereditary hemolytic anemias (e.g., diploic expansion, cranial bossing, and maxillary hyperplasia in β -thalassemia and bone infarcts in sickle cell anemia) are clear, such bony changes are seldom reported in the clinical literature for other forms of anemia. Notwithstanding, early reports have noted cranial and postcranial skeletal changes associated with chronic IDA that are consistent with the erythroid hyperplasia and/or ineffective erythropoiesis seen in the chronic form of this disease. Indeed, any form of anemia with associated erythroid hyperplasia and/or ineffective erythropoiesis (severe iron, B_{12} , and folate deficiency, for instance) could, in theory, lead to these types of skeletal changes.

In the bioarchaeological and palaeopathological literature, two cranial lesions, porotic hyperostosis (PH) and cribra orbitalia (CO), are often attributed to IDA (see Oxenham and Cavill 2010). While there is clinical evidence suggesting that some of the anemias could lead to the type of lesions that characterize PH, there is currently no clear clinical evidence that CO is a bony response to any of the anemias. It is, however, theoretically plausible that diploic expansion and cortical bone thinning in the orbital roof could be caused by erythroid hyperplasia and/or ineffective erythropoiesis in response to IDA, some of the HAs, and megaloblastic anemias in infants and children. Nonetheless, a single common etiological pathway linking PH and CO has yet to be found. PH aside, a range of other conditions have been theoretically or clinically linked to the various forms of expression of CO, including pseudopathologies, subperiosteal inflammation due to a range of infections (Wapler, Crubezy, and Schultz 2004), scurvy (Brickley and Ives 2006), and orbital hematomas of various aetiologies (Ma'luf et al. 2002). In paleopathological cases, the differential diagnosis for these types of cranial (including orbital) lesions will include a wide

range of conditions, invariably including IDA, HA, and megaloblastic anemia. Nonetheless, given current issues in clearly identifying the underlying etiology of PH and CO, it is perhaps best to simply treat these lesions as skeletal signatures of nonspecific physiological stress unless additional overwhelming evidence suggests one etiological pathway over another.

SEE ALSO: Bioarchaeology; Congenital Conditions; Differential Diagnosis; Human Growth and Development; Humanity and Animality; Malnutrition; Metabolic Disease; Paleopathology; Parasitology

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Bioarchaeology

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Today, the field of bioarchaeology is generally understood to encompass a broad range of methodologies that extract biological and cultural information from archaeological human skeletal remains. Although the term was first applied in the broader context of any biological data recovered from archaeological sites, such as paleobotanical remains (see PALEOETHNOBOTANY), faunal remains (see ZOOARCHAEOLOGY), and other indicators of paleoenvironment (Clark 1972), this usage has given way to a narrower focus on human skeletons and mortuary contexts as a source of data. The term “bioarchaeology” was first applied to human remains in this sense by Buikstra (1977). Thereafter, the field emphasized the bridging of biological and cultural data obtained from human remains, especially as applied in a populational perspective. Thereby, bioarchaeology was distinguished from the traditional descriptive osteological report typically published as an appendix to an archaeological site report and from “osteobiography” (Saul 1972) that emphasized individual life histories. This new discipline was situated in the more evolutionary context of population biology that laid the framework for the “New Physical Anthropology” (Washburn 1951) and was also allied with the growth of processual archaeology. Thus, one can consider bioarchaeology to be an endeavor that bridges between physical (biological) anthropology and archaeology.

Despite focusing on human remains as a source of biological data, bioarchaeology emphasizes the cultural context of human remains and archaeological theory building as sources of research hypotheses. Hence, bioarchaeological research designs of the later twentieth century, and, in particular, North America and the United Kingdom, emphasized the use of skeletal data to address cultural questions about

major demographic transitions, such as the adoption of agriculture (Cohen and Armelagos 1984), the arrival of Europeans in the Americas (Larsen and Milner 1994), and the emergence of social complexity (Steckel and Rose 2002). The new millennium has seen a return to questions of individual life histories and biocultural aspects of identity, and has embraced studies of paleomobility and population genetics.

Osteology and paleodemography

Bioarchaeology is rooted in the study of the human skeleton, called osteology (see OSTEOLGY), and begins with the excavation of human remains in archaeological sites (see BURIAL EXCAVATION and COMMINGLED HUMAN REMAINS) and an attempt to understand the mortuary or funerary context (see MORTUARY ANALYSIS) in which they were encountered. In addition to evaluating the depositional history of the remains, human osteologists attempt to identify the age at death and skeletal sex of the remains they examine.

For remains that are not skeletally mature, age is typically estimated by reference to dental development (see ESTIMATING SUBADULT AGE: DENTAL DEVELOPMENT AND ERUPTION), growth of limb bones (see ESTIMATING SUBADULT AGE: DIAPHYSEAL LENGTH), or maturation of epiphyses (see ESTIMATING SUBADULT AGE: EPIPHYSEAL UNION). Ongoing research in human skeletal biology and growth and development has led to a variety of new methods and standards for such age assessment in recent years. For remains of adults, the age-related deterioration of the skeleton occurs more variably; however, research continues to refine methods to assess age using the cranial sutures, pubic symphyses (see ESTIMATING ADULT AGE: PUBIC MORPHOLOGY), and auricular surfaces of the ilium (see ESTIMATING ADULT AGE: AURICULAR SURFACE MORPHOLOGY), among other features. Recent publications emphasize Bayesian statistical treatment of skeletal age characteristics to obtain probabilistic estimates of age at death (see ESTIMATING ADULT AGE: TRANSITION ANALYSIS).

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Identification of sex from skeletal remains is usually limited to adult skeletons or those nearing skeletal maturity. Dimorphic features of the cranium and pelvis (see ESTIMATING SKELETAL SEX: CRANIAL AND PELVIC MORPHOLOGY) are most useful for sexing adult skeletons, although metric dimensions of the postcranial skeleton (see ESTIMATING SKELETAL SEX: METRICS) are also useful if appropriate population-specific reference data are available. Although some skeletal features may be dimorphic in children, considerable interpopulation variation and conflicting study results lead most workers to shy away from making such assessments. However, sex assessment using ancient DNA is quite promising (Faerman et al. 1998) (see CHROMOSOMAL DNA).

Age and sex assignments form the basic data used in paleodemography (see PALEODEMOGRAPHY), especially life table (see LIFE TABLE ANALYSIS) and hazards analyses (see PALEODEMOGRAPHY AND HAZARDS ANALYSIS). Together with archaeological indicators of population growth and decline, paleodemography gives considerable insight into the population dynamics of past societies through time, and the consequences of human adaptation to environmental contexts.

Biodistance

Human remains provide the possibility of understanding the evolutionary relationships between ancient societies and peoples. Such “biodistance” studies (see BIOLOGICAL DISTANCE) attempt to measure the extent of biological separation, and conversely the shared ancestry and intermixture among ancient skeletal remains across both geographic and chronological space. Until the last few decades, such work emphasized the size and shape of the cranium (see CRANIOMETRY) and teeth (see DENTAL METRICS) as well as morphological traits of the skeleton and dentition (see DISCRETE TRAITS). Both approaches have helped flesh out population dynamics in prehistoric North America and Europe. Recent advances in the recovery, authentication, and interpretation of genetic material from ancient skeletons (see GENETICS: ANCIENT) and teeth have begun to provide more detailed understanding

of human diversity than was possible from early studies of mitochondrial DNA alone (see DNA: NEXT GENERATION SEQUENCING). New methods for sequencing DNA, called “next generation sequencing” (see DNA: MITOCHONDRIAL), now permit rapid sequencing of many fragments of DNA from a single sample, which ultimately allows reconstruction of partial genomes (see GENOMICS: ANCIENT) and more detailed biodistance analysis of ancient remains.

Paleomobility

Geochemical approaches to document population movement are an important new complement to paleodemographic and biodistance research. Ratios of the stable isotopes of strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) (see MOBILITY AND STRONTIUM ISOTOPES) and lead ($^{207}\text{Pb}/^{204}\text{Pb}$, $^{208}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{204}\text{Pb}$) (see MOBILITY AND LEAD ISOTOPES) are incorporated into bone mineral in proportion to their abundance in foods. Since these ratios reflect the geological origins of soils on which plant foods have grown, they preserve a geological signal in the bone or tooth mineral. Similarly, stable oxygen isotopes reflect the geographic and climatological origin of water imbibed, and are an important complement to the above methods. The stable isotope ratios of oxygen ($\delta^{18}\text{O}$) (see MOBILITY AND OXYGEN ISOTOPES) provide an important additional source of paleomobility data, but are affected by nursing and cultural practices, so are somewhat more challenging to interpret than the heavy Sr and Pb isotopes.

Paleodietary reconstruction

Direct measures of food consumption through chemical analyses of human remains have flourished since the 1980s. An early focus on the relative concentrations of the alkaline earth elements (strontium, barium, and calcium) in bone mineral (see DIET AND TRACE ELEMENTS) has given way to measurement of stable isotope ratios in bone collagen and tooth and bone mineral. Elemental analysis has been put aside largely due to concerns about both the effects of diagenesis

(elemental exchange with the burial environment (see *DIAGENESIS OF BONE*)) on alkaline earth ratios and uncertainty about interpretation of observed patterning. Diagenesis can also be a problem for isotope ratios; however, isotope signatures are somewhat more straightforward to interpret. Stable carbon isotope ratios ($\delta^{13}\text{C}$) (see *DIET AND CARBON ISOTOPES*) in bone collagen and skeletal mineral reflect the intake of foods with disparate content of the two stable isotopes of carbon, ^{13}C and ^{12}C . Such $\delta^{13}\text{C}$ ratios vary among plants due to enzymes used in varied photosynthetic pathways. This approach has been especially helpful in the Americas where maize (*Zea mays*) stands out as nearly the only major ancient cultigen with a distinctive $\delta^{13}\text{C}$ ratio. Stable nitrogen isotope ratios ($\delta^{15}\text{N}$) of animal tissues are enriched in ^{15}N compared to the proteins consumed, and therefore measure sources of dietary protein (see *DIET AND NITROGEN ISOTOPES*). A newer addition to the isotopic toolkit, the stable isotopic ratios of sulfur in bone collagen ($\delta^{34}\text{S}$), is useful to isolate proteins from aquatic sources in the diet (see *DIET AND SULFUR ISOTOPES*). Together, these methods have enabled a much more precise understanding of food intake by individual participants of the past, and of ancient paleoecology.

Infant feeding and childhood growth

Paleodietary research that compares carbon and nitrogen isotope signals in skeletons of differing ages at death has shed light on the diets of infants and children and developed into the study of breastfeeding and weaning in the past. This approach has been extended to include the use of oxygen isotopes (see *INFANT FEEDING*) in dental tissues, which form in infancy and childhood, allowing researchers to track water intake, nursing, and dietary changes during childhood within an individual.

The consequences of infant feeding and nutritional practices on health through the lifespan have been a longstanding interest in bioarchaeology (see *INFANT FEEDING*). Infant health has been studied both by examining the remains of infants and through the study of dental enamel hypoplasias, which are defects formed in tooth

enamel due to growth arrest during childhood (see *DENTAL DEVELOPMENT*). Completed skeletal stature (see *STATURE ESTIMATION*) provides a long-term index of growth achievement. Together, these approaches shed light on the processes of morbidity and mortality that form the basis of demographic change in ancient and modern societies.

Paleopathology

Evidence of ill health during life is often recorded in the skeleton; however, it is important to underscore that most morbid conditions leave little mark on the skeleton (see *PALEOPATHOLOGY*). Although some conditions, such as certain bone cancers (see *CANCER*) and congenital conditions, leave distinctive skeletal features (see *CONGENITAL CONDITIONS*), most nutritional (see *ANEMIA* and *MALNUTRITION*) and metabolic (see *METABOLIC DISEASE*) conditions leave much less obvious signs in the skeleton and most infectious conditions (see *INFECTIOUS DISEASE*) cause non-specific bony reactions. Careful differential diagnosis (see *DIFFERENTIAL DIAGNOSIS*) of skeletal anomalies is necessary to identify the health challenges affecting past communities. In the unusual case where soft tissues are preserved through mummification, imaging studies may aid diagnosis (see *IMAGING IN HUMAN REMAINS*), and parasites may also be preserved in or on the body (see *PARASITOLOGY*). Dental caries, abscesses, and calculus deposits can provide indications about oral health (see *ORAL HEALTH*) and dietary practices.

Behavior

Paleopathology may also shed light on past physical activity and behavior. For instance, bones fracture in characteristic ways depending on the stresses they are placed under (see *TRAUMA*), and their occurrence is unequal among archaeological skeletal populations. Similarly, bony joints degenerate with age and repetitive motion (see *DEGENERATIVE JOINT DISEASE*). Together with study of muscle attachment sites that remodel when placed under functional pressures (see *MUSCULOSKELETAL STRESS MARKERS*),

bone architecture and cross-sectional geometry (see CROSS-SECTIONAL GEOMETRY) reflect behavior and activity to a degree, and may shed light on differing lifeways at the population or subpopulation level.

There has also been considerable interest in cultural modifications of the human skeleton since the earliest archaeological work, and intentional cranial shaping (see CRANIAL SHAPING) and esthetic decoration of the teeth (see DENTAL DECORATION) continue to be frequent subjects of bioarchaeological work. Recently, these have been key components of archaeological theory building that emphasizes exploration of ancient ideas of embodiment (see EMBODIMENT) and the symbolic role of the body in cultural discourses of the past.

Ethics

Bioarchaeology too must grapple with ethical questions concerning how the study of human remains intersects with culturally appropriate treatment of the deceased, often requiring considerable efforts at collaboration and negotiation with descendant communities. Often, repatriation of remains may be required after study, a compromise that makes clear the need for detailed and standardized data recording of osteological, chemical, and genetic data such that these would be available for future comparative study.

SEE ALSO: Bodies and Embodiment; Coprolites; Embalming; Heritage and Human Rights; Human Growth and Development; Human Lives and Deaths; Human Skeletal Geochemistry; Sampling Theory; Sequencing DNA; Three-Dimensional (3D) Facial Reconstruction; Zooarchaeology and Ancient DNA; Zooarchaeology and Human Trade and Migration; Zooarchaeology and Stable Isotopes

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Biological Distance

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Biological distance analysis, or biodistance, uses phenotypic variation as a genetic proxy to reconstruct evolutionary mechanisms and patterns of biological diversity in past human populations. As such, the approach generally shares the same goals as anthropological genetics, with an emphasis on intraspecific (within species) microevolutionary interpretations (see *GENETICS: ANCIENT*). Biological distance uses heritable phenotypes, that is, metric and nonmetric variation of the cranium and dentition, as the basis for evolutionary inferences. At the broadest scale, patterns of global phenotypic variation help identify the process of modern human emergence and migration throughout the Old and New Worlds. For example, biodistance has contributed to our understanding of the peopling of North and South America, the peopling of Polynesia, and the repopulation of the Green Sahara. At the smallest scale, biological distance analysis can be used to determine whether two individuals buried together were biological kin or not. A key feature of biological distance analysis is scalability, from the micro to the global (Buikstra, Frankenberg, and Konigsberg 1990), which requires careful consideration of data collection protocols.

Four classes of biodistance data are recognized: craniometric, dental metric (odontometric), cranial nonmetric, and dental morphological. Each class of biological distance data has its strengths and weaknesses. Craniometric data analysis has the deepest history within the field, a history steeped in notions of skull collecting, race science, and typology. While modern craniometric analyses avoid such criticisms, the patina still remains and it is important to recognize that dental anthropology and cranial nonmetric anatomy do not share the same historical trajectories.

Metric data are recorded using established protocols, increasingly with intensive three-dimensional imaging and data capture techniques

(see *IMAGING IN HUMAN REMAINS*). Craniometric data collection is based on well-known osteometric landmarks (see *CRANIOMETRY*). Odontometric data typically comprise length and breadth measurements of the tooth crown and neck (see *DENTAL METRICS*). Analyses of metric data are simpler due to the ratio scale nature of these variables; however, theoretical concerns about the importance of size and shape should be considered (see *MULTIVARIATE ANALYSIS*). Ratio scale data are amenable to standard multivariate statistical analysis, as well as the more theoretically grounded R matrix analysis (Relethford 2007).

Cranial nonmetric data are anatomical variants of the skull that include variation in cranial ossicles (extra bones in the sutures), the number and formation of foramina, and hyperstotic (excess bone) and hypostotic (underdeveloped bone) skeletal features (see *DISCRETE TRAITS*). Dental morphology refers to anatomical variation of the tooth crown and roots, including extra cusps and enamel projections near the crown margins and neck. Both cranial nonmetric and dental morphological traits are recorded in a discontinuous scale that includes nominal and ordinal data types. As such, these traits are often dichotomized into binary variables for the purposes of frequency estimation. The discontinuous scale, however, complicates statistical treatments and until recently such data were not amenable to more theoretically grounded approaches such as R matrix analysis.

The basic assumption of biodistance analysis is that two closely related individuals are more phenotypically similar to each other than two unrelated individuals. By extension, two populations that exchange mates regularly are more similar to each other than two isolated populations, and the same is true of two populations that share a more recent common ancestor. Providing justification for these assumptions has been difficult. Many appeal to published studies of inheritance patterns for the different classes of biodistance data, despite the difficulty of interpreting what these estimates actually mean. Studies comparing the concordance of phenotypic and genetic data at multiple scales

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(von Cramon-Taubadel and Weaver 2009), from the global to the inter individual, do support the validity of these basic assumptions. However, further work is needed to understand the genetic coding of phenotypic variation and the sources of environmental noise that result from how the body develops within a framework that includes both genetic and nongenetic mechanisms.

A number of archaeological questions can be answered with biodistance analyses. At the scale of regional inference, analyses of phenotypic variation can be used to reconstruct patterns of migration and gene flow, ancestor–descendant relationships, population replacement events, population boundaries, and mortuary variability related to cemetery use practices (Larsen 2015). Intracemetery approaches also address a number of questions relevant to archaeology (Stojanowski and Schillaci 2006). Spatial analysis of phenotypic variation (see SPATIAL ANALYSIS) can reveal how a cemetery was organized and provide evidence of the existence of biological lineages, which can inform fine-grained studies of health and status. Comparison of male and female phenotypic variation speaks to postmarital residence practices, which have implications for understanding ancient social organization. More recent approaches have incorporated biological distance analysis into studies of ethnicity and social identity by emphasizing the relevance of marriage and mate exchange within the broader social world of humans.

Despite being an imperfect proxy for genetic sequence data, biodistance offers a number of benefits, including its nondestructive and relatively cost- and time-efficient nature, its ability to sample the populations of interest and model temporal changes directly, its statistically

tractable sample sizes, and its universal applicability regardless of host DNA preservation or contamination.

SEE ALSO: Bioarchaeology

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Burial Excavation

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When viewed through both time and space, human groups have demonstrated a vast diversity in their approaches to the disposal of their dead. While the dead end up buried in the earth in many societies, there are many other ways of disposing of bodies—such as exposure or disposal at sea—that do not leave archaeological traces. Burial is a form of disposal that involves remains being placed in the ground and covered over but there is significant diversity here too as burials can take many forms: inhumations; cremations; primary deposits; secondary deposits; ossuaries; mummies; bog bodies. Burials can provide a direct and tangible link to individual actors in the past and have always had a high profile both in the discipline and at the level of popular culture. This high profile is partly due to the fact that while death is a biological event, it is also a cultural experience that can provoke profound responses. Despite the fact that mortuary contexts link biological and cultural domains in this way, burial archaeology has had a chequered history in the discipline. Like antiquarian studies before it, the culture-history approach of the first half of the twentieth century had a strong focus on elite burials. Artifacts and architecture tended to be privileged in this approach. If they were curated, human remains retrieved from these contexts were used extensively in typological studies of racial difference. While these approaches had declined by the time of the development of the processual approach to archaeology, mortuary contexts were the focus of important theoretical advances linking funerary behaviors to their social contexts (e.g., Brown 1971). While the study of elite burials continued, particularly in relation to theorizing about social status, the move to processualist perspectives led to a democratization of burial archaeology. The development of interpretative approaches

since the 1980s has seen the further broadening of theoretical scope and one of the outcomes of this has been what Nilsson Stutz and Tarlow (2013) have characterized as a recentring of mortuary contexts in archaeology. This is in no small part due to the interdisciplinary approach championed by bioarchaeology, a subdiscipline that emerged in the late 1970s as part of the “New Archaeology.” Bioarchaeology has played an important role in promoting integrative approaches to graves and their contents (Rakita 2014), and archaeology as a whole has moved from relating cemeteries to parameters such as territoriality or the control of resources to a broader view that includes seeing these locations as reflections of past cosmologies.

Excavation

While theoretical landscapes and recording methods have changed considerably in recent decades, the excavation of a burial is still done in ways that would have been familiar to early twentieth-century archaeologists. Burial excavation is a fascinating process that creates an intimate triangular link between people who lived in the past, unborn generations of the future, and the excavator. This is because once a burial has been fully excavated, the process cannot be repeated as excavation is destructive. Excavators therefore have an ethical obligation to make sure that their recording system is comprehensive, systematic, and permanent. This ensures that future generations will be able to examine their work in fine detail and reevaluate interpretations if necessary.

The process of excavation begins with the identification of a grave cut. This is the outline of a pit dug in the past and backfilled once the remains, burnt or unburnt, had been placed in the ground. Most excavations proceed stratigraphically which means that buried features are usually excavated in a sequence that is the reverse of their deposition. The grave backfill is removed first, taking care to identify and preserve the edges of the

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grave cut. Human remains will be encountered usually at the base of the grave fill and should be left in situ until all of the bones are exposed and recorded. While trowels are usually used to excavate down to a burial, they are not the ideal tool for the excavation of skeletal remains. Smaller tools such as a mason's leaf should be used. Soil samples may be taken during the excavation process for analyses of factors such as the presence of intestinal parasites, where the earth lying immediately over the sacrum of a skeleton is collected along with a control sample taken from behind the skull. Care should be taken that any artifacts present in the burial should also be left in situ so that their precise location and associations can be recorded.

Recording burials

The burial must be comprehensively recorded prior to lifting the remains and this usually involves creating paper and photographic records along with detailed, scaled drawings. Standardized forms are often used for each skeleton as well as for each context uncovered during the excavation. Photographs are taken with a scale, an arrow indicating where north is located and a storyboard with information about the burial such as site name, date, and burial number. There have been important methodological advances in how archaeological burials are recorded. The process has been revolutionized by technologies such as photogrammetry and 3D scanning. While the latter involves equipment that not all projects can access, all that is required in the field for photogrammetry is a good camera and if proper protocols are followed, hand drawings are not needed. These methods have the added benefit of reducing the time between the uncovering of burial contents and their conservation. Three-dimensional models of burials can be scaled and georeferenced for placing them in geographic information systems (GIS). This allows for the digital reconstruction of stratigraphy as well as the production of highly accurate site plans. Similarly, 3D scanning of artifacts and human remains allows for the creation of digital museums that can facilitate greater access to data while reducing the deterioration of the

originals. One important contribution that relies on very precise recording in the field is the approach developed in France, *L'Antropologie "de Terrain"* (Duday et al. 1990). This has the goal of distinguishing between cultural behaviors and taphonomic changes in the disposition of remains.

Lifting burials

Once a burial has been recorded, the excavator gently loosens the remains from the soil. Remains are not prised out of the ground but gently freed from the earth surrounding them and placed in clearly labelled bags. These should be prepared prior to lifting the remains and each bag should be labeled with indelible pen with the site name, year of excavation, burial number, and the skeletal elements contained in the bag. The main parts of the skeleton should be bagged separately, distinguishing between each side. The remains are then transferred from the field to the lab where they are washed, dried, and rebagged in a similar way before being boxed, ideally in a sturdy plastic crate, for long-term curation. Poorly preserved or delicate remains should be dried, wrapped in acid-free paper and then bagged and boxed.

Changing views of burials

Early twentieth-century archaeologists tended to pay more attention to burial architecture than to buried bodies. In turn, the processual approach to grave architecture was dominated by formal analysis. More recent approaches to burial-related monumentality stress meaning as well as form. Similarly while artifacts may also have been privileged over other elements in burials in the past, recent approaches have been more holistic and insights regarding materiality have framed much of the discussion regarding grave goods. Rather than being viewed as static signifiers of factors such as status or gender, grave goods have been recast as mediators of social relations and are understood in a more dynamic manner that stresses the agency of objects. Explorations of funerary practices in archaeology have also been transformed by insights from social theory with

a stress on the contextual and dynamic nature of ritual.

Approaches to archaeological burials have also been transformed by explicit theorizing of the body. Burial archaeology has made a significant contribution to the dynamic theoretical perspectives that have emerged around the archaeological body. Phenomenological approaches played an important role in transforming perspectives of the body in the archaeological imagination. These placed an emphasis on the physicality of the body and its interaction with the material world. While undeniably biological and physical, the archaeological body is also understood as something formed by cultural processes: the body is molded by a lifetime of performance of culturally-constructed roles (Sofaer 2006). These performances occur in architectural settings and in relation to material objects, a perspective that brings together elements of burial archaeology that were previously considered independently. Incorporating bioarchaeological data has also transformed the manner in which we look at archaeological bodies. The manner in which bioarchaeological research tended to analyze individual skeletons in order to pool data to discuss populations has prefigured narratives of the individual versus the collective body. Integrative approaches to mortuary patterning of age, sex, and pathology (a two-way process that has influenced bioarchaeological praxis) have opened discussions on issues such as how we conceptualize health and ill-health in the past, care, disability, social deviance, childhood, and social age. There has been significant discussion of gender and a rejection of simplistic equations with particular grave goods, arguing instead for approaches that look critically at theories of human action. Contemporary arguments for nonbinary views present interesting challenges for understanding the performance and experience of gender in past societies and demand critical reflection. Equally, new insights from techniques such as DNA and stable isotopes challenge us to consider the relationship between bodies and objects in new ways. Both of these techniques have yielded data on issues such as the movement of people in the past and cultural practices such as matrilocality and patrilocality. Isotopes have also yielded significant data on dietary practices. The very fact that archaeologists engage with graves from the

past shows that death is not the end: memory of the dead is important in many societies. From the “working dead” (Laqueur 2015) to the political lives of dead bodies (Verdery 1999), the dead can remain a powerful force among the living. Through a combination of all of these elements, the archaeology of mortuary contexts can provide insights into lived experiences, identities, and power in past societies.

Traditional burial archaeology has had a big influence on forensic archaeology. This influence is not a one-way process with non-forensic archaeological approaches benefiting from work carried out for judicial purposes. Projects such as the Body Farm (Bass and Jefferson 2004) have informed approaches in the retrieval of non-recent remains while forensic work on mass graves, along with the emergence of the archaeology of the contemporary, has paved the way for the recently articulated Holocaust archaeologies.

These interesting changes and the increased recognition of the importance of mortuary contexts have occurred against a backdrop of the increased politicization of archaeological burials. Resistance to the excavation of graves, as well as to the long-term curation of artifacts and particularly the human remains contained therein, emerged partly as a backlash against cavalier attitudes by archaeologists and others in the past but also as a result of the increasing empowerment of descent groups in the post-World War II era of decolonization. In 1989, the World Archaeological Congress sponsored an “inter-congress” at Vermillion, South Dakota around the theme of “archaeological ethics and the treatment of the dead.” The resulting Vermillion Accord on Human Remains (WAC 1989) placed the wishes of the dead, where they can be ascertained, along with those of local and descent communities on a par with the scientific research value of the remains. This code influenced the development of policies in a number of world areas, not least in the United States where the Native American Graves Protection and Repatriation Act (NAG-PRA) was enacted in 1990. While high-profile controversies have continued over some sites and assemblages, these initiatives have fostered debate around issues of ethics and respect—for the living and the dead—in many world areas.

SEE ALSO: Archaeology and the Present;
Bioarchaeology; Bodies and Embodiment;
Digital Photogrammetry; Gender and Sexuality;
Human Lives and Deaths; Material Agency;
Mortuary Analysis; Paleopathology;
Parasitology; Repatriation; Taphonomy

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Cancer

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Cancer is the generic name given to those tumors that have the propensity to spread from their site of origin to other parts of the body, and for this reason they are referred to as malignant. Benign tumors, by contrast, do not spread but remain in their parent tissue. Tumor spread may be local or distant, affecting almost any organ of the body, including the skeleton. The original tumor is known as the primary tumor, while those that spread are referred to as secondary tumors or metastases. There are two principal types of cancer: carcinomas—tumors that arise in epithelial tissues such as those that line the inner or outer surfaces of the body; and sarcomas—tumors that arise from the supporting tissues of the body; *stricto sensu* they arise in cells derived from mesenchyme. Carcinomas are by far the most common type.

Cancer is ubiquitous among animals and is concomitant with multicellularity, since with each cell division there is a possibility that errors arise in the DNA that in some cases may lead to malignant change. Cancer cells are not subject to the normal controls on cell division and on programmed cell death; hence these mechanisms do not limit the growth and spread of cancer cells.

There is no reason to suppose that humans (and other animals) have not been subject to malignant changes from the earliest times. Relatively few cases appear in the paleopathological literature, because cancer is, *par excellence*, a disease of the elderly. Cancer is rare below the age of 60, but thereafter its incidence rises steeply with increasing age, so that by the age of 80 almost everyone has a tumor somewhere. It is not likely that, until recently, many individuals lived into the ages at which cancer is common. The age- and sex-specific prevalences of malignant disease in the past were probably similar to those of today (Waldron 1996),

although it is likely that the distribution of tumor types was different owing to differing habits and exposures to putative carcinogens in the environment.

Perhaps a more significant reason for the rarity of tumors in the archaeological record is what one might call the problem of attrition. This can best be appreciated from an example. In the first annual report of the registrar general for England and Wales, almost 356,000 deaths were recorded for the year July 1, 1837–June 30, 1838. This number for one single year is far greater than the total number of human remains that have been examined from this country, which lessens very considerably the chances of finding any remains with evidence of cancer. And then, when one considers how nonrandom the process of recovering human remains is and that a relatively high proportion of them are incomplete, lacking precisely those elements that are most likely to be affected by secondary tumors, then it is a wonder that any evidence of cancer is found at all.

Secondary tumors of bone

Secondary bone tumors are many times more common than primary bone tumors and, although almost any primary tumor may spread to the skeleton, some show a much greater predilection to do so than others. The primary tumors that most often affect bone are those arising in the thyroid, kidney, breast, lung, and prostate. Thyroid and kidney tumors are the ones most likely to invade the skeleton but, since they are not nearly as common as breast, lung, or prostate cancer, secondaries from the last three sites make up the greatest proportion of skeletal tumors. Spread to the skeleton tends to take place via the lymphatic or venous systems, but the various regions of the skeleton are by no means equally likely to be affected. Thus secondary bone tumors tend to be found in the skull, spinal column, pelvis, and proximal femur. Secondary bone tumors are rarely found in the bones of the arm, hand, lower leg, and foot.

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Secondary tumors typically produce either lytic or sclerotic lesions—and sometimes a mixture of the two. Those that are lytic secrete cytokines such as RANKL, which stimulate the production and activity of osteoclasts, to the point of causing holes in bones. The most dramatic effects of secondary tumors are often seen as multiple holes of varying sizes in the skull. The lesions have ragged, undercut edges with no signs of healing, and in life would have been filled with tissue from the primary site. The radiography of affected bones will almost always show a number of radiolucent areas that represent lesions within the substance of the bones that are not visible to the naked eye, as well as lesions that have destroyed the cortex.

There is no way in which secondary tumors of the breast or lung (or indeed of any other site) can be differentiated in the skeleton; the diagnosis must be based on probability. Thus lesions found in a male are much more likely to be from a lung primary, for, although breast cancer does occur in men, it is much less frequent than lung cancer. Conversely, lesions found in a female are more likely to be from a breast primary, since breast cancer is more common in women than lung cancer. It is never possible to be dogmatic in a particular case, however. There is also an alternative diagnosis that needs to be borne in mind, and that is of multiple myeloma. This is a malignant disease that arises from plasma cells in the bone marrow, and it, too, causes holes in bones through the production of cytokines that stimulate osteoclasts. The lesions appear in exactly the same places as lytic secondaries from other primaries and, in practice, it is impossible to differentiate between them on morphological grounds. Some authors claim that the lesions produced by myeloma cells are more regular in size than those caused by breast or lung secondaries. Myeloma cells produce an abnormal immunoglobulin, called myeloma protein, in great quantities in the blood and in urine, where it can readily be detected. Myeloma protein might survive death and burial and has been detected at least once in a skeleton (Cattaneo et al. 1994); its presence, of course, will confirm a diagnosis, but its absence is not helpful one way or the other.

Tumors of the prostate act to stimulate osteoblasts, thereby causing sclerotic secondaries through the production of cytokines, together with the production of quantities of immature

bone. Bones containing prostatic secondaries will appear normal but may be slightly heavier than usual. In the spine, for example, some of the lower thoracic or lumbar vertebrae may seem heavier than their neighbors and radiography may show dense new bone within them. These may be difficult to differentiate from Paget's disease. A rare form of prostatic cancer has been reported in the paleopathological literature simply because it forms periosteal new bone in abundance throughout the skeleton (Waldron 1997). It is likely that more cases of prostatic cancer would be detected if the skeletons of elderly males were routinely X-rayed.

Primary bone tumors

Primary bone tumors are exceptionally rare, being slightly more common in males than in females. In the present-day population of the United Kingdom, their incidence is approximately 8.5 per million in males and 6 per million in females. Three types account for virtually all primary bone tumors: osteosarcoma, chondrosarcoma, and Ewing's sarcoma. Osteosarcoma and Ewing's sarcoma are tumors that predominantly affect children and young adults, their peak incidence occurring between the ages of 5 and 20. For osteosarcoma, there is also a much smaller peak in old age in a minority of individuals with Paget's disease who develop malignant change in some of their affected bones. Chondrosarcoma is rare in the young, but its incidence increases steadily with advancing age. Osteosarcoma is the most common type of primary bone tumor (some 47 percent of the total) and is followed by chondrosarcoma (33 percent); Ewing's sarcoma accounts for the remaining 20 percent.

Each type of tumor tends to have a different skeletal distribution. Most osteosarcomas occur in the long bones of the leg, especially around the knee joint. The remainder may be found in almost any other bone. These rapidly formed masses occur on the external surface of the affected bones and often have a characteristic X-ray appearance, described as a "sunburst." Chondrosarcomas, by contrast, favor the pelvis and the axial skeleton and develop within the bone substance. Their presence may be suggested by subperiosteal

deposits enlarging affected bones. Ewing's sarcomas develop as lesions within the long bones, including the clavicle, with consequent localized periosteal expansion on the affected bones. Plain radiography or computerized tomography (CT) scanning of unusual lesions on bones should be undertaken wherever possible and may aid in diagnosis. Even with the help of an experienced skeletal radiologist, however, firm diagnosis may be impossible; modern-day pathologists rely on histological evidence to come to a conclusion, but, of course, such evidence is not available to the paleopathologist, who works with skeletal remains.

Cancer in mummies

Mummies provide the paleopathologist with a much higher chance of making a positive diagnosis of a primary tumor, although the internal organs are not always present, or not always well preserved. The problem of attrition is even greater with mummies, but there are cases in the literature that should nevertheless encourage the continued search for evidence (David and Zimmerman 2010).

The diagnosis of cancer in human remains

In the vast majority of cases, paleopathologists will be dealing with skeletal rather than mummified remains, in which case the diagnosis of cancer is one of the probabilities rather than a certainty. There are many diseases that may give rise to lytic lesions in bones, but fortunately most of them are unusual or rare (Waldron 2009). It is important, however, to have some knowledge of the prevalence of those conditions that may mimic cancer in the skeleton, so that a realistic assessment may be made of their likely appearance. However trite, always bear in mind that common things occur commonly and, conversely, rarities are seldom seen.

There are almost no ancillary investigations that will help in making a diagnosis. Radiography is sometimes instructive, particularly with those tumors that may be contained within bone, of course, but it proves to be disappointing more

often than not. It is possible that, some time in the future, we will be able to extract molecular or genetic markers of cancer, but this is not likely to be an option for the paleopathologist in the near term.

SEE ALSO: Bioarchaeology; Differential Diagnosis; Imaging in Human Remains; Paleopathology

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Chromosomal DNA

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What are chromosomes?

DNA consists of two chains of base pairs wound into a double helix. A base pair is a pair of complementary bases, consisting of a purine in one strand linked by hydrogen bonds to a pyrimidine in the other. Cytosine always pairs with guanine, and adenine with thymine (in DNA, or uracil in RNA). Some 3 percent of the DNA consists of genes that confer a trait; the rest is so-called junk DNA without clear purpose (some claim that it acts like scaffolds to the genes). Nuclear DNA, or chromosomal DNA, includes part or all of the genetic material (genome) of an organism. Gametes are an organism's reproductive cells. Female gametes are called egg cells, and male gametes are called sperm. Gametes are haploid cells, meaning that each cell carries only one copy of each chromosome. Chromosomal DNA is found inside the nucleus of a cell, and its quantity varies widely between different organisms. Humans have 46 chromosomes, of which 22 pairs are called autosomes, which look the same in both males and females. The 23rd pair, the sex chromosomes, differs between males and females (the Y-chromosome and the X-chromosome, respectively). One set of chromosomes for each pair comes from a person's mother, and the other set of chromosomes comes from the father. This inheritance pattern is very important and is in stark contrast to the way mitochondrial DNA is inherited, which is solely from the mother, and the Y-chromosome is inherited, which is solely from the father. Although most of the DNA is packaged in chromosomes within the nucleus, the mitochondria also have a small amount of their own DNA. The mitochondria are structures within the cells suspended in the cytoplasm that convert the energy from food into a form that cells can use as energy (i.e., adenosine

triphosphate, ATP). When scientists speak about sequencing whole genomes, they are speaking about the chromosomal DNA, as the mitochondrial DNA (mtDNA) is only a small part of the human genome (3.2 billion base pairs vs. 16,500 base pairs) (see DNA: MITOCHONDRIAL).

The history of ancient DNA

At the beginning of ancient DNA research (see GENETICS: ANCIENT), only mtDNA was used due to its abundance (thousands of copies) and ease of replication (it is very short). In 1983, Mullis developed a technique that mimics the cell's own DNA replication process; he called it polymerase chain reaction (PCR). By using this technique, a single copy or a few copies of a segment of DNA can be amplified, generating thousands to millions of copies of a particular DNA sequence. The first real use of chromosomal DNA in archaeology came in 1996 when the first chromosomal DNA was used to determine the sex of several archaeological individuals based on the amelogenin gene. There is a difference of 12 base pairs (bp) between the gene on the Y-chromosome versus the gene on the X-chromosome (Stoneking 1996). This technique has since been used regularly throughout the 1990s and into the 2000s, especially when osteologists cannot tell whether skeletal remains are female or male (see OSTEOLOGY). Even though researchers had shown that nuclear DNA could be extracted and analyzed, nothing much changed during the next 10 years, and mitochondrial DNA was predominantly used; what little chromosomal DNA sequences could be analyzed were often disputed. The main issue was initially the authenticity and/or origin of the ancient chromosomal DNA. Many sequences were too damaged or short and thus were hard to identify. Adding to this, scientists were using human archaeological remains, and this made it difficult to separate modern contamination from authentic ancient DNA. This contamination could come from chemical reagents, the archaeologists/

osteologists/geneticists themselves, or from the burial environment of the remains.

Genetic markers

In 2005, a number of studies reported the successful recovery of ancient chromosomal DNA sequences that allowed the characterization of genetic loci directly involved in phenotypic traits of extinct taxa. For the first time, the field of ancient DNA could show what extinct species might have looked like. This was groundbreaking and soon led to a flurry of research targeting easy genetic loci that involved phenotypic traits, such as skin and hair color (e.g., *MC1R*, a receptor that plays an important role in pigmentation), and adaptive traits, such as lactose intolerance. It is true that the great majority of phenotypic characteristics are complex traits, complicating the identification of the genes underlying their expression, but for some we now know the underlying mutations due to genome-wide association studies.

Point mutations or SNPs

A single nucleotide polymorphism (SNP) is a DNA sequence variation occurring commonly within a population (e.g., 1 percent) in which a single nucleotide (A, T, C, or G) differs between members of a biological species or paired chromosomes. Before the introduction of next-generation sequencing (NGS), SNPs were predominantly used for looking for both changes in the chromosomal DNA and phenotypic expressions. Next-generation sequencing changed all of this, making it possible to look at whole genomes or thousands of SNPs. All of this new data has made it possible to study admixture, population origins, and the like (see *DNA: NEXT GENERATION SEQUENCING*).

The melanocortin 1 receptor (MC1R)

One of the key proteins involved in regulating mammalian skin and hair color is *MC1R*. The receptor is primarily located on the surface of melanocytes, which are specialized cells that produce a pigment called melanin. The skin or hair

color can change based on a single point mutation. This SNP has a different location for different mammals, making it very useful for a wide range of studies. Since 2006, it has been steadily used in archaeological studies to determine the coat colors of mammoths, cattle, horses, dogs, pigs, as well as the hair color of the Neanderthals and ancient humans (Linderholm and Larson 2013).

Lactose tolerance

Normally we lose our ability to digest the milk sugar lactose by the time we stop breastfeeding. However, the ability to consume milk as an adult occurs at high frequencies in present-day populations, coinciding with the practice of dairying and cattle rearing. Genetic frequency maps show that northern Europe has the highest frequency of lactose tolerance. Sweden has the highest incidence, with over 70 percent lactose tolerance. This is an adaptive trait that has undergone an enormous positive selection, possibly driven by gene-cultural co-evolution. The -13910*T allele associated with this trait (in Europeans) seems to have been subjected to strong selection over a relatively short period of time. It was first detected in ancient population samples in 2009, and since then has been used to track the introduction of dairying across Europe (Malmström et al. 2010).

Admixture

One of the most pervasive debates in archaeology was whether or not the Neanderthals and modern humans interacted with each other. Early data from mtDNA did not show this to be the case. However, the only way to truly investigate admixture is by looking at chromosomal DNA (to detect DNA signals from both parents). Initially, long or even shorter fragments of chromosomal DNA from ancient materials seemed to be much harder to obtain than first thought. So SNPs were first targeted in order to be able to use chromosomal DNA for archaeological admixture analysis. By using SNPs, shorter fragments of chromosomal DNA could be utilized. By using this approach, genome-wide SNP data (that is, SNPs from across the whole genome) from both contemporary populations and extinct hominins were generated

to examine potential admixture events in prehistory. The datasets obtained strongly support a single dispersal of modern humans from Africa, followed by two archaic admixture events: one with Neanderthals somewhere outside Africa, and a second with Denisovans in Asia. By using chromosomal DNA, the long-lasting debate has been dissolved; we now have solid evidence for an admixture between not only modern humans and Neanderthals, but also with Denisovans.

Chromosomal DNA and validity

For the most part, the authenticity of the results from chromosomal DNA was still an issue. To resolve this, a group of scientists published a paper in 2006 about assessing the fidelity of nuclear ancient DNA, comparing it with mtDNA; they found that they behaved very similarly, despite great differences in cellular copy numbers (one nucleus vs. thousands of mitochondria) (Binladen et al. 2006). That is, the postmortem damage patterns are the same regardless of DNA source; the authors showed the existence of miscoding lesion damage in both mtDNA and chromosomal DNA, resulting in insertion of erroneous bases during amplification. This type of damage pattern can now be used as an authentication method when using NGS. However, care still needs to be taken when working with allelic variation and the confidence in single nucleotide polymorphism identifications.

Genomes and next-generation technology

Whole genomes are a great source of information, due to the recombination that occurs in each generation, so one whole genome could potentially represent a whole population. A genome is an organism's complete set of DNA, including all of its genes. Each genome contains all of the information needed to build and maintain that organism. Two technological innovations made the study of ancient whole genomes possible, and both happened early in 2000: next-generation sequencing and DNA hybridization enrichment. Together, these resulted in multifold increases in

both the quantity and the quality of ancient chromosomal DNA sequence data. The sequence data output went from 0.7× coverage (mammoth) in 2008 to more than 50× coverage (Neanderthal) in 2014. Coverage (or depth) in DNA sequencing is the number of reads that covers a given nucleotide in the reconstructed sequence. The time depth for DNA retrieval has also been pushed backwards by using this technique; the oldest to date is a horse dated to approximately 560–780 thousand years before present (Orlando et al. 2013) (see GENOMICS: ANCIENT).

The future

The last couple of years have seen an explosion in whole genome assemblies. DNA sequence assembly is a process through which short DNA sequence fragments (called reads) are merged into a longer DNA sequence in an attempt to reconstruct the original DNA sequence. We now have hundreds of them (from humans, animals, and other organisms), spanning both time and space. The possibility of what we can study seems endless; we can identify and track rapid evolutionary changes, such as the evolution and spread of pathogens and the genetic responses of hosts, or slower events such as the genetics behind domestication and climatic adaptation. New statistical methods and modeling programs used to analyze the genetic material are developing swiftly, and the importance of paleogenomics for investigating evolutionary processes during the last million years is likely to increase considerably in the future.

SEE ALSO: DNA: Mitochondrial; DNA: Next Generation Sequencing; Genetics: Ancient; Genomics: Ancient; Osteology

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Commingled Human Remains

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Commingled human remains can be defined as the mixing of the elements of multiple individuals into a single archaeological or forensic context. This can occur through both natural and cultural mechanisms, and usually both will have an effect on the way archaeological assemblages can be examined. Both archaeological and forensic assemblages are discussed, with an emphasis on how the creation of the assemblage will affect possible analyses. Assemblages can be broken into three different categories: (1) long-term usage (those used for multiple depositional episodes, typically across generations); (2) episodic usage (those used for single depositional events resulting from the deposition of multiple individuals at a single time in a single deposit); and (3) lab commingling (unintentional commingling of individuals that occurs during analysis and storage). Finally, a short discussion of analytic methodology is included. Important to keep in mind with any analysis of commingled remains is that there is no *right* way to analyze a commingled assemblage; methodology will depend on the research questions of the analyst.

Long-term usage assemblages are typically the result of primary and secondary interments from community groups. Primary interments are the initial interments of the body, usually occurring shortly after death. These may be disturbed or altered to produce a secondary interment. An example of secondary interments may include bundled bones collected from primary interments. Assemblages resulting from accretional primary burials will have different archaeological representativeness than those resulting from the periodic gathering of primary burials into a secondary assemblage. Primary assemblages will be based on the placement of primary burials into a collective tomb or grave with the addition of

more primary burials on top of previous burials. This type of assemblage will have an adequate representation of smaller elements, though through time these smaller elements may filter to the bottom of the assemblage due to normal shifting of elements and decomposition of the primary burial. Assemblages resulting from the gathering of skeletal elements for deposition in a secondary burial will have fewer small elements since these are more difficult to recover. Elements of newer burials are added to the mass containing older elements. Because of the attritional aspects of this type of assemblage, smaller elements such as hand and foot bones may filter to the bottom of the assemblage or may be poorly represented as they might not have been collected from primary burials. Often, a mixture of primary and secondary burials will be present in a long-term use assemblage, such as that typified by Tell Abraq, a Bronze Age ossuary dating to 2200–2100 BCE in the United Arab Emirates. The representativeness of hand and foot bones was used as a proxy measurement of primary versus secondary deposition for this assemblage. It was determined to have approximately 30 percent of the expected number of hand phalanges, suggesting primary depositions of individuals that were allowed to decompose naturally before being moved to the edges of the tomb to make room for additional burials and burial bundles.

Episodic usage assemblages can be best thought of as assemblages resulting from mass burials. These may be the result of plague, sacrifice, or warfare, any activity that will result in the death of multiple individuals at a single time. They are, therefore, episodic in nature, versus a longer term accretional assemblage like that discussed previously. Characteristics of these assemblages may include minimal commingling, depending on the natural processes present. If significant earth pressure or earth movement is not present, little or no commingling may be present. If they are buried in a location close to the surface or with heavy bioturbation (disturbance by living organisms such as insects as well as scavengers), commingling may be severe. Element representation is typically consistent

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with the demography of the burial population. Demography will also reflect processes leading to the creation of the assemblage: for example, epidemics are expected to affect the very young and very old more than young adults. In the case of epidemic commingled burials, fears of contamination are also a factor in the creation of the assemblage. For example, burials associated with epidemic outbreaks may only be given rudimentary burial rites—they may be placed in a communal grave without coffins or other signs of social rank such as grave goods. This may result in increased commingling when combined with taphonomic factors such as earth movement and bioturbation. Epidemic burials may also be hurried and make use of existing pits or unused structures such as mine shafts.

Warfare burials may also form episodic burials. Examples of this include the Battle of Little Bighorn/Greasy Grass (nineteenth-century America) and the Battle of Towton (fifteenth-century Yorkshire). Battlefield assemblages may have increased levels of commingling due to intentional postmortem mutilation or processing of the remains (e.g., mutilation of commanders and trophy taking). Demography of such assemblages will also vary depending on combatants. It is expected that assemblages resulting from warfare will contain more adult and adolescent males than females. Raiding activity may also result in episodic burials that show commingling, however. The taking of women and children as captives doesn't always lead to their incorporation into new communities. Brooks (2016) details an eighteenth-century massacre of the village of Awat'ovi (in modern-day Arizona) in which the women and children were led away from the village toward other villages after the mass killing of most of the males of the community. At some point, a decision was made to kill the captives and their commingled remains were recovered in nearby Polacca Wash in the twentieth century. Raiding may also occur when young males were not present, so demography of mass graves resulting from this type of raiding would be unlikely to have those individuals represented in significant numbers.

Assemblages resulting from ethnic cleansing and genocide would also fall under the umbrella of episodic assemblages. The United Nations General Assembly codified genocide as a legal

concept as the intentional destruction of a specific group based on national, ethnic, racial, or religious affiliation. The demography of such a mass grave may be key to an identification of a genocidal assemblage, since it is expected to contain all individuals of the selected group. These assemblages may contain perimortem injuries and postmortem processing. These assemblages are thoroughly explored in Adams and Byrd (2014).

Commingled assemblages from the American Southwest provide a useful example. Assemblages exhibiting extreme processing (Kuckelman, Lightfoot, and Martin 2000) are episodic commingled assemblages. These include the case studies present in Turner and Turner's (1999) *Man Corn* as well as the Sacred Ridge assemblage (Osterholtz 2013). These assemblages have signs of defleshing and dismemberment as well as extensive commingling of individuals. These assemblages have been interpreted by some as indicative of cannibalism (e.g., White 1992), terrorism (e.g., Turner and Turner 1999), witchcraft executions (e.g., Darling 1998), and politically motivated massacres with performative overtones. Episodic assemblages may also be the result of postmortem processing of the dead as part of a mortuary program, cooptation of ritual space and land tenure (see case studies in Osterholtz, Bausation, and Martin 2014). Manipulation of the dead may be important for the construction of social status and identity, regardless of how it occurs.

The final type of commingling occurs in the laboratory or field during analysis or curation. While this is unintentional, lab commingling can complicate analysis for numerous reasons, primarily the loss of excavation information and context. When commingling occurs in the course of the creation of an archaeological deposit, such as that at Tell Abraq or Sacred Ridge (a Southwestern assemblage dating to approximately AD 800), the mapping of the deposit can create location data that can be added to the bony data to understand how the deposition occurred and allow for more thorough interpretation of the assemblage. When this contextual information is lost through lab commingling, analysis can be severely limited. The use of excavation photos and notebooks can be useful in determining the degree of lab commingling and the untangling of lab commingled deposits.

Methodologies for the analysis of commingled remains varies based on the research questions of the researcher. Due to the nature of the assemblages, baseline data must first be determined, and then this can be used for secondary analyses. Baseline data, such as the minimum number of individuals (MNI) and the demography of the assemblage (sex and age at death distribution), can be difficult to determine, but are useful in the overall interpretation of the assemblage. It is through the identification of the demography of some assemblages that epidemic mass graves can be identified, for instance. Determining MNI is a complicated process, particularly in assemblages with significant fragmentation, such as those exhibiting extreme processing. The author argues for a feature-based approach for the determination of MNI, where individual skeletal features are identified for each fragment and tallied to determine MNI. This method of MNI determination will give an overall MNI based solely on the duplication of features; the MNI should be then examined based on the demography. It is therefore important to choose features for the determination of MNI that are sexually dimorphic and will give at least some indication of age at death of the individual. For Sacred Ridge, over 50 features were recorded for the entire skeleton. In particular, over 20 features on the skull were recorded. Other methods for the determination of MNI are essentially also based on the duplication of elements. Hermann, Devlin and Stanton (2014), for instance, have used a 3D scanning technique that allows for the overlay of individual fragments to determine how many elements are present by stacking the 3D images to look for overlapping elements. This method does not rely on the identification of features, and while requiring significant computer resources and time, provides a very accurate determination of MNI.

SEE ALSO: Bioarchaeology; Human Skeletal Data Quantification; Infectious Disease; Mortuary Analysis; Taphonomy

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Congenital Conditions

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The term “congenital” refers to physical traits, usually pathological, that are already present at birth. This category captures a wide spectrum of developmental conditions, including syndromes such as Down syndrome, and major malformations such as cleft palate and polydactyly. Loosely defined, it also includes developmental variants, minor anomalies that may become more apparent with age. Etiologically, congenital conditions are diverse, resulting from genetic mutations, exposure to teratogens, and maternal health factors during pregnancy. As a result, the interpretive value of congenital conditions in anthropological contexts varies according to the type of condition and the factors responsible for its occurrence. Although congenital conditions may affect any system of the body, here we focus primarily on those syndromes, major malformations, and minor variants that are manifest in the skeleton and are therefore identifiable in archaeological contexts.

Most syndromes and major malformations are thought to be quite rare in the archaeological record when compared to their frequencies in modern clinical studies. One explanation might be infanticide of the malformed, resulting from cultural ideas about the nature and viability of individuals with specific conditions. In other cases, premature mortality, differential burial, or issues of skeletal preservation might be to blame for the low frequencies. Whatever the cause, most syndromes and birth defects identified in the archaeological record are discovered incidentally.

Several dwarfing syndromes have been identified in archaeological contexts, including achondroplasia, the most common form of dwarfism today. Achondroplasia is a bone

growth disorder characterized by disproportionate dwarfing of the limbs, primarily affecting the upper arms and legs, relative to the trunk. Achondroplastic dwarfs also exhibit a bulbous forehead, midface hypoplasia, bowed legs, and hand anomalies. Approximately 1 in 40,000 people are affected today, most due to spontaneous mutations to the FGFR3 gene, but the condition may also be inherited from an affected parent. Though diagnosis of a specific dwarfing condition out of 100+ known possibilities can be difficult, achondroplasia has been proposed to explain most archaeological cases. Dozens of affected skeletons are known worldwide, and numerous artistic depictions of dwarfs have been identified in ancient Egypt and Greece (Dasen 2013). In Egypt, artistic and textual evidence indicates that some dwarfs held positions of religious and administrative significance, including oversight of the royal wardrobe and pets. The potential for dwarfs achieving high status in society is supported by the interment of several near the pyramids at Giza and Saqqara, and at the site of Abydos.

Trisomy 21, commonly known as Down syndrome, typically occurs due to nondisjunction of the 21st chromosome. Affected individuals exhibit nonskeletal manifestations such as intellectual disability and developmental delay, along with a suite of possible skeletal characteristics including a short broad head, depressed midface, small jaw, and shortened digits. In addition, dental indicators may include missing teeth, tooth transposition, or dental crowding. Trisomy 21 is the most commonly occurring genetic syndrome in humans, with a rate of approximately 1 in 700 births in the United States. Despite this, extremely few cases of trisomy 21 have been identified in the archaeological record. Reasons for the paucity of affected individuals from archaeological contexts may include infanticide, shortened lifespan, and a lower incidence of Down syndrome in antiquity. The frequency of trisomy 21 is influenced by maternal age, and ranges from about 1 in 2,000 for 20-year-old mothers to 1 in a 100 by age 40. If fewer mothers lived into their 40s in the past, then the probability of Down syndrome would also be reduced.

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While all of these reasons may account, in part, for the lack of skeletons with trisomy 21 in the archaeological record, the discrepancy between the modern incidence of dwarfing conditions and trisomy 21, relative to their identification in the archaeological record, is still surprising. We should not assume that infanticide, as a culture-dependent practice, or the lower average age of mothers would fully explain the lack of individuals with trisomy 21 in antiquity. After all, most affected individuals today are born to younger mothers, simply because younger individuals are more likely to reproduce. Furthermore, women in past societies may not have had effective means to control conception at older ages. Indeed, the discrepancy between the number of dwarfs and the number of trisomy 21 cases identified in ancient skeletal material probably says more about osteological training than about people from the past. It would be difficult to overlook the dramatically short height and unusual limb robusticity found in achondroplasia, for example, while the physical manifestations of trisomy 21 are subtle and occur, albeit in lower frequencies, in the population at large.

Major congenital malformations occur sporadically in the archaeological record. They may include cranial defects such as cleft lip/palate, or malformations of the limbs or trunk. In some cases, these conditions have clear detrimental impacts on the likelihood of survival. Individuals with cleft lip/palate, for example, often have difficulty breastfeeding, reducing their likelihood of thriving without assistive measures. Despite this risk, dozens of archaeological cases of cleft palate are known dating from as early as the Neolithic. Of course, folk interpretations of congenital malformations vary by society and time period. In Medieval Europe, cleft lip was often attributed to maternal impression, whereby the sights, emotions, and experiences of a pregnant woman could affect the form of her infant. By this way of thinking, a woman who gave birth to an infant with cleft lip was believed to have thought about or seen a hare, or a similarly affected individual during pregnancy, hence the derogatory term “harelip.”

In some severe congenital malformations, affected individuals may exhibit shortened lifespans. Two such life-threatening conditions are anencephaly and spina bifida, which are related neural tube defects affecting the brain and/or

spine that can result from both genetic and environmental factors, including low maternal folate (vitamin B9) levels during pregnancy. Anencephalic individuals have incomplete formation of the brain and skull and few survive more than a few days after birth. Perhaps partly due to taphonomic and cultural biases that may inhibit their recovery and identification, anencephalic individuals are extremely rare in the archaeological record (Dudar 2010). Discovery of an anencephalic individual in a collection of mummified baboons from ancient Egypt suggests that the individual may not have been considered fully human.

Spina bifida, a malformation characterized by failure of the neural tube to fully close, may involve hydrocephaly, mental deficiencies, and partial paralysis in cases of protrusion of the spinal cord. The degree of mobility impairment and the impact on life expectancy varies depending on which part of the spine is affected. An adolescent with spina bifida of the lower spine from the archaeological site of Windover in Florida also displays evidence of lower limb infection, disuse atrophy, and loss of the right foot that together indicate sensory deficits, ulceration, and the loss of mobility seen in this 7,500-year-old skeleton (Dickel and Doran 1989).

Polydactyly, characterized by extra fingers or toes, is another major malformation that is reported much less often archaeologically than its modern frequency might predict. Most studies suggest rates in various populations between 1 in 100 and 1 in 1,000 births. The reasons for infrequent reporting probably relate to a number of factors, the most important being that extra digits are usually considerably underdeveloped in most individuals and hard to recognize in isolation. Therefore, polydactyly is difficult to identify in archaeological skeletons unless the relevant bones are undisturbed during recovery. Among the limited number of reported polydactyly cases from antiquity, the Southwestern United States seems to be the region with the greatest number (Case et al. 2006). Widespread depictions of both hands and feet with sixth digits also occur in Southwest rock art and Mesoamerican iconography. Because polydactyly has both a genetic and a nutritional component, either (or both) might explain the higher frequency in the Southwest.

Another condition that may affect the foot is talipes equinovarus, commonly known as clubfoot. Individuals with talipes equinovarus display a downward-pointing heel and inward-facing sole affecting both the bones and associated soft tissues of the foot. While the occurrence of clubfoot varies by population, it is seen on average in 1 in 750 births, with males affected more often than females. Both genetic and environmental factors appear to be associated with idiopathic clubfoot. A bilateral case was recently reported from the Mayan site of Tikal in Guatemala (Wright 2011). However, despite the skeletal involvement, relatively few cases have been reported archaeologically, given modern frequencies of the condition.

Minor congenital variants are much more common and are frequently asymptomatic. Many, including tarsal coalition and vertebral malsegmentation, are unlikely to have been recognized in life. Both of these conditions occur due to failure of bones to separate during embryonic and fetal development, resulting in the union of adjacent bones via fibrocartilaginous or osseous tissue. These conditions may occur in isolation or as part of a syndrome. Malsegmentation of the second and third cervical vertebrae, for example, is unlikely to be noticed in a living individual, but some affected individuals with the condition have Klippel–Feil syndrome and also display a webbed neck, congenital elevation of the shoulders, and an additional bone between the spine and scapula.

Tarsal coalition, a congenital malsegmentation anomaly between adjacent bones of the ankle and foot, is asymptomatic in most affected individuals. However, increasing evidence of population variation in its occurrence can be useful in anthropological contexts. Recent analyses suggest the existence of population-specific patterns of expression that may be useful in examining population movements. For example, known cases of tarsal coalition among ancient Native Americans correlate with patterns seen in East Asian samples, indicating that patterns seen in native New World populations may originate from Old World Asian ancestors prior to the peopling of the Americas (Burnett and Wilczak 2012).

Minor anatomical variants have also been used to identify genetic relatedness among individuals in archaeological contexts. Among

these are dental conditions such as hyper- and hypodontia—numeric anomalies of the dentition characterized by supernumerary and congenitally absent teeth. Of course, the value of a genetic trait increases based on its heritability and frequency. Hypodontia of third molars is rare during much of hominin evolution but has increased over the past 10,000 years. Today, third molar agenesis may occur in up to 30 percent of humans due to evolution favoring a smaller jaw. This high frequency renders the trait less useful for identifying related individuals in a cemetery, except as one of a larger suite of traits. Conversely, extremely rare congenital variants can be very powerful for identifying genetic relatives. Enlargement of the parietal foramina, located at the upper rear portion of the skull, is estimated to occur in only 1 out of 25,000 individuals. Identification of 11 cases of this condition at a small, prehistoric archaeological site from California has been used to infer relatedness among the affected individuals, and two more cases at a site nearby suggests intermarriage or population movement (Hoffman 1976).

SEE ALSO: Biological Distance; Differential Diagnosis; Human Growth and Development; Paleopathology

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Coprolites

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Coprolite, a paleontological term of ancient Greek origin for ancient fossilized feces, was first applied to human fecal material in 1890. While these specimens, also called paloe-feces, were noted in sites from many regions by early archaeologists, there was little research on coprolites until the 1960s, when Eric O. Callen rehydrated them in a 0.5 percent trisodium phosphate solution. This technique allowed for the systematic study of the constituents of the coprolite. Even after this development, many archaeologists still did not recognize the research potential of these screen-clogging specimens, generally discarding them and even using them as Frisbees for lunchtime entertainment (Bryant and Dean 2006). As archaeologists become more interested in the ecological underpinnings of past societies, coprolites became an important dataset for understanding past diets and environments.

Coprolite formation

Coprolites are biochemically complex specimens that contain residues derived from multiple sources. Fry (1985) lists six major components: (1) undigested dietary compounds; (2) intestinal secretions of the individual, including hormones; (3) minerals and other substances excreted into the digestive tract; (4) hindgut bacteria and their metabolic derivatives; (5) cellular components, including parasites and pathological evidence; (6) enteroliths, gallstones, pancreatic calculi, and fecal spherulites. While this complexity offers a high variety of potential lines of data, the majority of coprolite studies have focused on the identification of food residues and parasites.

Coprolites represent a temporally limited window into the dietary decisions of an individual.

This record of food combinations is unparalleled as a detailed record of meals. This is furthered by the biological complexity of the specimens themselves, which allow for direct dating and for many lines of evidence on diet. However, coprolites are preserved only under conditions of desiccation, waterlogging, or freezing. Most coprolites are recovered from protected sites, such as rock shelters and architectural structures.

Macroscopic analysis

The most abundant components of many coprolite specimens are macroscopic plant and animal remains such as seeds, fiber (see FIBERS), bone (see BONES AND IVORY), hair, chitin, and scales. These components can inform us on diet but may not accurately reflect the relative importance of different food items. This is particularly true of easily digestible plant and animal components such as the soft tissue of fruits, geophytes such as tubers, skeletal muscle and other tissue from animals, or plant foods that are heavily processed before consumption, such as milled seed resources.

Microscopic analysis

Since the first studies by Paul Martin in the 1960s, pollen analysis (see PALYNOLOGY) has become a routine part of both human and animal coprolite studies. Pollen analysis is perhaps most useful in identifying the possible medicinal ingestion of plants (Chaves, De Miranda, and Reinhard 2003), though it has also been used to infer seasonality and diet.

Ova and larvae of both ectoparasites and endoparasites are the second most common microscopic component identified in coprolite studies (see PARASITE OVA AND CYSTS; Araújo, Reinhard, and Ferreira 2015). It should be noted that interpretations of these remains must be made with caution, as many parasite ova are difficult to classify or are not exclusive

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to humans. Evidence of parasitic infestation can provide an excellent means by which to evaluate changes in community health that occurred with the development of agriculture or were due to increasing population density (see PARASITOLOGY).

Other microfossils have also been recovered from coprolite specimens: phytoliths (see PHYTOLITH ANALYSIS), starch (see STARCH GRANULE ANALYSIS), bacteria, fungal spores, and diatoms (see DIATOMS). Phytoliths (mineral structures formed in plant tissue) are the most frequently studied of these microfossils and are a better proxy for food consumption than pollen, as they may come directly from the plant tissues that were desirable foods.

There have been few attempts to look for starch in coprolites. Starch granules are direct evidence of past diet, since the starch itself is the nutrient being consumed. Starch is a highly digestible carbohydrate in the human gastrointestinal system, but research has shown that there is a great deal of variability in the digestibility of starch—which is influenced by the molecular structure of the starch itself, the complex interaction of starch with other cellular components of the food resource and of the rest of the meal, and the processing techniques involved in meal preparation.

Biochemical analysis of coprolites

The dietary data derived from the macroscopic and microscopic residues of coprolites is unparalleled in the archaeological record. Concordant lines of evidence inform on the dietary decisions underlying the meals represented in the specimen. This extremely detailed access into the decisions of an individual actor in the past is furthered by a range of molecular techniques that have been applied to coprolites.

Coprolites contain a range of organic and inorganic substances, as well as compounds at varying stages of digestive breakdown. Infrared absorption spectroscopy (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)) has been employed to study the chemical composition of mineralized human feces. Other possible techniques for characterizing chemical compounds

include gas chromatography–mass spectrometry (GC/MS) (see GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS)), which can also be used to monitor the light stable isotope ratios of individual compounds.

Immunosorbent assay

This technique is frequently applied to modern fecal specimens and can be used to detect a number of antigen proteins, depending on the research goal. It has been used primarily to detect evidence of parasitic infection. This technique has also been used to confirm the consumption of human flesh associated with evidence of human butchery at Cowboy Wash, Colorado (Billman, Lambert, and Leonard 2000).

aDna

Human mtDNA from coprolites can provide direct evidence of past movement of human populations and other questions of paleodemography through the evaluation of the common haplotype groups among populations. Studies at Paisley Cave have used mtDNA from coprolites to document a pre-Clovis occupation (Gilbert et al. 2008).

Much of the work on animal and plant DNA in coprolites has focused on nuclear and chloroplast DNA, since nonhuman mtDNA has a limited capacity to inform on dietary choices (see CHROMOSOMAL DNA). There are some exceptions, such as the identification of turkey domestication in the American Southwest through mtDNA markers (Speller et al. 2010). While many nuclear DNA fragments cannot be identified below the family level, corollary evidence from macroremains and microremains can improve the resolution of the resulting interpretations. Despite recent interest in gut microbiomes and the preponderance of these organisms in coprolite specimens, no attempt has been made to examine the DNA of these communities.

Steroids

Before the advent of aDNA research, steroid analysis was the most commonly employed chemical technique in coprolite studies. The analysis of

these compounds can be used to address a number of research questions. Since humans produce species-specific sterols (a subgroup of steroids found in plants, animals, and fungi) in their feces, the analysis of these compounds can inform on the presence of human fecal material in water or soil or can verify a coprolite as human in origin. Because our sex hormones (estrogens and androgens) are steroids, determining the sex has been the primary focus of fecal steroid studies in human coprolite research (Sobolik et al. 1996). There may also be some potential for distinguishing between the follicular phase and the luteal phase in coprolites deposited by women.

Stable isotopes

While stable isotope studies are routinely conducted on preserved skeletal material from archaeological sites in order to study ancient diets, there are few published studies of stable isotope data derived from human coprolites. Staple carbon isotopes inform on the use of plant resources with differing photosynthetic pathways ($\delta^{13}\text{C}$; see DIET AND CARBON ISOTOPES), while nitrogen isotopes shed light on the role and source of animal protein ($\delta^{15}\text{N}$; see DIET AND NITROGEN ISOTOPES). The relationship between dietary $\delta^{13}\text{C}$ values and the resulting $\delta^{13}\text{C}$ values of feces is complex, since fecal material represents a combination of indigestible dietary residue, the bacterial flora of the gastrointestinal tract, and cells of multiple tissue types from the individual. However, one major advantage of fecal $\delta^{13}\text{C}$ values is that they can be used to ask questions about changes in diet over much shorter time periods than the record found in bone and teeth, which represents a dietary average over a longer time span.

AMS c-14 radiocarbon

Coprolite specimens can be directly dated using accelerator mass spectrometry (AMS) radiocarbon methods. This is particularly important at sites that have been impacted by artifact collectors, looting, and animal grazing. Out-of-context specimens can be temporally associated using AMS radiocarbon dating. While coprolites do provide enough carbon to

be dated directly through traditional radiocarbon methods, there is potential for external contamination and admixture of components within the specimen. AMS dating allows for the direct subsampling of either the visible components or the general residue in the specimen without destroying a large portion of that specimen.

Coprolites are among the most biologically complex evidence of past human activity in the archaeological record. One specimen can yield multiple lines of congruent evidence on an individual's dietary choices, as well as information on seasonality of site occupation, overall health, parasite load, potential sex through sterol analysis, and even individual identity through mtDNA. This wealth of information focused on the actions of one individual over a day or two requires different frames of analysis from the archaeological palimpsest that results from the actions of multiple individuals over years and decades.

SEE ALSO: Chemistry in Archaeology; Food Residue Analysis; Organic Residue Analysis; Paleoethnobotany; Zooarchaeology

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Cranial Shaping

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The reshaping of the infant's skull counts as one of the most widespread and at the same time diversified body modification traditions in the human past. Cranial modification has been practiced in numerous areas and epochs on all continents, and has been especially well-documented in the Americas and Central Africa. Namely the Mangbetu from the Republic of Congo have practiced head elongation until recently by using constricting cords, a technique which is similar to the head modifications among indigenous peoples from the Pacific Islands. On the Eurasian continent, head modifications were practiced by multiple means and were still common in subscribed areas, such as southwest France, until the beginning of last century.

Cranial modification took place in the first few years of an infant's life while the skull is still malleable; at the age of two to three years the skull hardens and the shaping became permanent. The artificial modification of the infant head was therefore performed on newborns, babies, and toddlers. It was practiced mostly by female kin who used for this purpose daily head massages by hand, compression cradleboards, head splints, soft constricting wraps and bandages, constricting hats, or a combination of these compression devices. Most plastic modifications of the skull targeted the neurocranium exclusively, although permanent facial flattening is reported in the literature as a rare form of permanent head embellishment (Dingwall 1931, 197). Cranial vault modification appears to be a very ancient practice that goes back to hominid forms predating *Homo sapiens* (Tiesler 2014).

Cross-culturally, head shaping related to a myriad of motives related to child rearing, identity, ethnicity, status, and gender, or more vaguely, tradition and beauty. In particular, the notion of embellishment by actively shifting the head's

morphology linked its enactment and visible outcome to culturally aligned ideas of the body, physical embodiment, and constructed beauty (Bonogofsky 2011; Lock and Farquhar 2007). The public display of heads with their altered morphologies have lent themselves to studies of body discourse, performance, and body display, in which the head is regarded as a physical recipient of socially mediated action, a social canvas, that represents society as it assimilates self-assigned group identity. These concepts and other humanistic research on the relationship between the head and society, touch upon notions of physicality and corporeity, corporeality, material interaction, self-reflection and representation, and cosmological models.

Apart from such social "construction," recent inquiries of cranial shaping among archaeologically retrieved cranial series tend to be craniometric in scope and have established themselves as a formal line of research in anthropological and health-related sciences alike. Physiologically speaking, extrinsic modifications of cranial morphology are brought about in infants and small children. They are accomplished by means of massages, constriction and/or compression over prolonged periods of time. The external pressure does not cause any passive tissue retreat, but rather results in compensatory neurocranial expansion that induces the brain and the cranial vault to expand towards unrestricted areas. Natural limitations to externally-induced morphological change are induced by the maturation and/or hardening of the cranial and related connective tissues, which increasingly limit plastic change after the first couple of months of life. Apart from maturation, health risks in treated minors depend on the degree and technique of the applied extrinsic forces and the location of compression vectors on the cranium. Secondary effects may include focal infections, necrosis, and bleeding, and—albeit rarely mentioned—intracranial hypertension.

The permanent nature of most cranial modification allows scholars to study the skeletal and broader contextual record for understanding the processes involved and their possible

Table 1 Classification of artificial cranial modifications (Tiesler 2014, 72). Adapted from Dembo and Imbelloni (1938, 275).

Type	Generic compression device	Degrees [0–4]	Distribution of compression (in degrees ≤ 3)	Circular wraps [0–3]	Sagittal constriction [0–3]
Tabular oblique modification	- Fronto-occipital compression effected by a head splint	- Extreme [>3] - Intermediate [≤ 3]	- Intermediate - Curved occipital - Curved frontal - Parallelepiped - Mimetic	- Absence - Presence of horizontal constriction (pseudo-circular)	- Absence - Presence of band [$>0-2$] - Bipolar separation [>2]
Tabular erect modification	- Posterior compression in supine position in a cradleboard	- Extreme [>3] - Intermediate [≤ 3]	- Intermediate - Occipital-plane - Frontal-plane Parallelepiped Mimetic Conical	- Absence - Presence of horizontal constriction (pseudo-circular)	- Absence - Presence of band [$>0-2$] - Bipolar separation [>2]
Annular modification	- Symmetric annular constriction through elastic bands, wraps, or hats	No information	No compression plane or flattening	No information	No information

The variables that are relevant for determining the compression types and techniques (first two columns) follow as four separate columns: They relate to the severity of cranial change, the distribution of compression planes, the presence of circular constriction, and the presence of sagittal constriction.

meanings. The analytical parameters for the study of head shaping practices are generally anchored in description, craniometrics, and adapted taxonomic criteria. These have been examined within regional cultural frames. A host of taxonomic criteria have evolved over the past 200 years to classify artificial head shapes in different areas of the world, namely in the Americas (Tiesler 2014; Table 1). Here, some of the early classifications attempted to correlate specific head shapes to ethnicity or social class or to their intentional or unintentional aesthetic nature (Dembo and Imbelloni 1938; Weiss 1961). The latter admits the possibility of head flattening being the unintended side product of cradleboarding and tumpline use, for example.

Further approaches have sought to infer the compression techniques from the specific changes they have left in the cranial morphology. Such an attempt was made by the Imbelloni system, which has been adopted widely by Latin American scholarship (Dembo and Imbelloni 1938; Table 1). This taxonomy distinguishes flexible bandaging and hat constrictions from hard compression kits. While flexible devices constrict head growth symmetrically and usually result in roughly symmetric and tubular cranial vaults, hard compression devices flatten the compressed surfaces and originate the bulging of uncompressed areas of the cranial vault.

Among the rigid compression kits, cradleboards are commonly identified with broad and short head silhouettes (tabular erect head shapes) and head splinting with long and inclined heads (tabular oblique cranial vaults) (Table 1). Despite this association between specific devices and corresponding head morphologies, an ongoing discussion targets the exact implementation of compression kits and their potential combination with strings and pads. Emphasis has been placed on the importance of overall skull form and the location of constriction grooves or compression planes.

In recent decades, 3-D landmark studies have replaced descriptions, plain measurements, and two-dimensional representations. These detailed three-dimensional records of ancient

skulls have allowed scholars to deepen their understanding of the dynamics involved in extrinsic cranial change. Such methods have also replaced uni-dimensional classifications with multivariate statistics and geometric modeling. These datasets and broader bioarcheological and contextual criteria provide useful points of departure for inferring the social dimensions and temporal trends of past head-molding practices.

SEE ALSO: Bioarchaeology; Dental Decoration; Embodiment

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Craniometry

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Craniometry, or the quantification and comparison of human cranial form (shape and size), has been a central methodology of anthropology for several centuries. However, the guiding motivations for and underlying theoretical assumptions regarding craniometric analyses have changed substantially over time. Historically, craniometric data were largely used as a means of generating and justifying essentialist racial classification schemes (Gould 1981). Particular emphasis was placed on studying the cranium (as opposed to other skeletal regions, see OSTEOLOGY), given its association with brain growth and the predominant assumption that brain size was directly related to cognition and intelligence. It is worth noting the distinction between craniometry and the popular nineteenth-century pseudoscience of “phrenology,” which advocated that external features of the skull reflected a person’s innate talents, abilities, and personality. Largely catalyzed by the work (*De Generis Humani Varietate Nativa*) of Johann Blumenbach (1752–1840), first published in 1775, large collections of crania were amassed across Europe and the United States with the purpose of creating objective and repeatable means of quantifying cranial variation. Hence, particularly during the nineteenth century, much effort was expended on identifying particular metrics that could be rigorously and repeatedly captured from human skulls. A classic example of such a metric is the cranial index defined by Swedish anatomist Anders Retzius (1796–1860). The cranial index is quantified as maximum cranial width divided by maximum cranial length, expressed as a percentage. This ratio is still widely used in bioanthropology and bioarchaeology (see BIOARCHAEOLOGY) today as a means of assessing whether cranial samples are relatively doliocephalic (i.e., long skull compared to width) or brachycephalic (i.e., short compared to width).

Under the direction of Paul Broca (1824–1880), the French school of craniometry emphasized the need for consistent means of quantifying cranial form, describing in detail “points de repère” (points of correspondence) that could be identified on the outer surface of the skull. Broca advocated the use of Greek terms for naming these points (landmarks) (Figure 1) and his naming scheme was expanded by subsequent workers, most notably Aurel von Török (1842–1912), Paul Topinard (1830–1911), and Felix von Luschan (1854–1924). In 1937, the American biological anthropologist, William W. Howells (1908–2005), reviewed definitions of craniometric landmarks as they stood at that time, and identified several different “schools” of craniometry. The German anatomist, Rudolf Martin (1864–1925), had expanded and amended von Török’s list, while in the USA, Aleš Hrdlička (1869–1943) and Harris Hawthorne Wilder (1864–1928) were the major authorities on craniometry. In Britain, the science of craniometry was largely directed by the Galton laboratory at University College London, which adhered strongly to the measuring scheme set out by the Frankfort Agreement. The Frankfort Agreement was an attempt to standardize craniometric schemes, reached during the 13th general congress of the German Anthropology Society held in Frankfurt-am-Main in August 1882. The final version of the agreement was published in the *Archiv für Anthropologie* in 1885. One major outcome of this agreement was a standard way to orientate the cranium when taking measurements using a plane drawn from the base of the two eye orbits and the top of the external ear opening. This plane, known as the Frankfort horizontal (Figure 1), is still in common usage today.

While the Frankfort Agreement went some way towards standardization, large-scale differences in craniometric methodology still abounded, such that another congress was organized in Monaco in 1906 in an attempt to finalize a common craniometric scheme that would receive widespread international recognition. However, this congress was only partially successful in terms of reaching a unanimous

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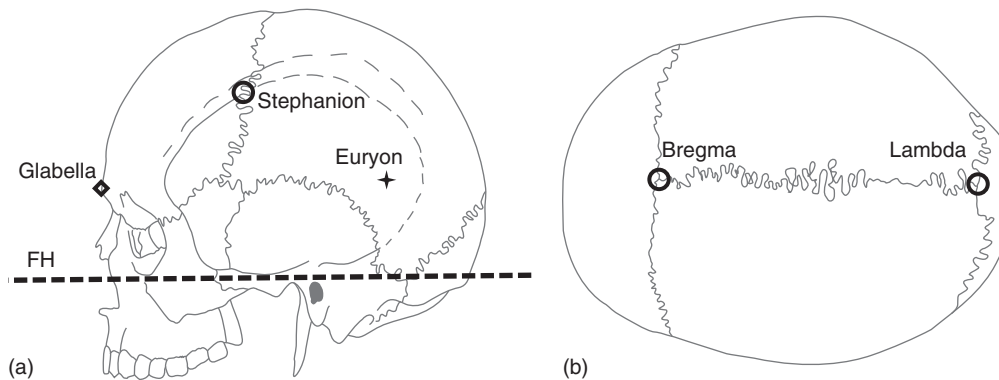


Figure 1 Human cranium in lateral (a) and superior (b) view showing the position of the Frankfort horizontal (FH) and five classic craniometric landmarks, which differ in terms of how they are defined. Open circles depict landmarks defined in reference to discrete anatomical features, such as suture intersections. Glabella (diamond) is defined as the most prominent point on the anterior median plane when the skull is in FH. Euryon (star) is defined purely as being the bilateral endpoint(s) of the greatest breadth across the skull, and is, therefore, defined on the basis of measurement and not by specific anatomical features.

agreement among researchers from different countries. Nevertheless, as a result of the industry of anthropologists such as Rudolf Martin (1914) and William Howells (1973), standardized schemes were developed with attendant detailed descriptions for how data should be taken in practical terms. William Howells was particularly influential as he laid out clear instructions on how landmarks should be identified (see Figure 1 for some classic cranial landmarks) and how measurements should be taken, as well as providing clear explanations as to how his definitions differed from those of other workers.

“Traditional” craniometrics, therefore, deals with the quantification and analysis of linear measurements (i.e., distances between two cranial landmarks), angles drawn between three landmarks, and ratios of linear measurements (see also MEASUREMENT THEORY). Typically, such traditional craniometric measurements are taken with a variety of handheld calipers designed to allow access to different parts of the skull. Many anthropologists follow the system outlined by Howells (1973), which includes the major dimensions of facial and cranial width, length, and chords and angles that describe the curvature of the major bones of the cranial vault. In 1996, Howells published his full craniometric dataset of over 2,500 crania representing 28 globally distributed human populations

(see HUMAN POPULATIONS). Hence, in the past 20 years, numerous studies have been published reanalyzing these data or using them as a comparative context for understanding patterns of cranial affinity between modern or past human populations. Most craniometric analyses involve the measurement and comparison of more than two traits (bivariate analysis) and are therefore considered multivariate analyses (see MULTIVARIATE ANALYSIS). Such analyses require the comparison of variance within traits and covariance between traits (see ANALYSIS OF VARIANCE AND COVARIANCE) as a means of quantifying the average differences in cranial form within- and between-groups. The potential differences in cranial form between individuals can then be visualized by decomposing a craniometric data covariance matrix using, for example, principal component analysis (see PRINCIPAL COMPONENT ANALYSIS). Alternatively, it is possible to convert the craniometric data into a between-groups distance matrix (see BIOLOGICAL DISTANCE), sometimes referred to as a biodistance matrix. The among-group affinity pattern coded in the distance matrix can then be visualized using methods such as principal coordinate analysis, multidimensional scaling or cluster analysis (see CLUSTER ANALYSIS) to see which groups resemble each other most closely in overall cranial form.

In recent decades, bioanthropologists have been turning to newer geometric morphometric (see GEOMETRIC MORPHOMETRICS) methods as a means of quantifying and visualizing the shape of different skeletal elements (see HUMAN SKELETAL DATA QUANTIFICATION). Geometric morphometrics operates by directly analyzing the covariance within configurations of landmark coordinates captured in two (x, y) or three dimensions (x, y, z). From a statistical viewpoint, traditional caliper-based methods can provide data that are just as powerful for capturing overall cranial shape as landmark-based methods, but the advantage of geometric morphometrics is the ability to visualize the shape transformation of the whole configuration simultaneously, rather than trying to interpret shape differences one metric measurement at a time. Landmark coordinates can be captured in two dimensions from photographs, or in three dimensions directly from the skull or mandible using a handheld digitizer. In recent years, researchers are increasingly using laser (see LASER SCANNING) or structured light scanners to capture 3D models of crania, which can then be virtually measured or landmarked. These scanning methods for capturing craniometric data are particularly useful in the case of archaeological remains which may be very fragmentary, as the method is noncontact and can also be used for the virtual reconstruction of incomplete cranial specimens. While traditional linear distance measurements can be directly compared from one cranial specimen to the next, in the case of landmark configurations it is first necessary to statistically transform the raw landmark (x, y, z) coordinates such that variation in the position of one landmark relative to the other landmarks can be quantified. The most common method for doing this is called generalized Procrustes analysis (GPA) and it works by translating all landmark configurations to a common origin, scaling each configuration to a single unit size, and then rotating each configuration such that the overall deviations between homologous landmarks are minimized. The resultant landmark coordinates (Procrustes variables) are now directly comparable across specimens and can be subject to standard multivariate statistical methods as described above.

In bioarchaeology, the most common type of analyses that utilize craniometric data are biodistance studies. The basic premise underlying

such analyses is that patterns of among-group craniometric affinity patterns reflect underlying patterns of neutral genetic variation. This premise is justified because numerous studies have shown that modern human cranial shape diversity patterns reflect neutral microevolutionary forces of mutation, gene flow, and genetic drift (von Cramon-Taubadel 2014). Moreover, the majority of standard craniometric traits are at least moderately heritable (Carson 2006). Hence, when samples of crania are found to resemble each other more closely, it is reasonable to assume that this reflects a closer degree of relatedness either because they recently diverged from the same ancestral population or because they have been exchanging migrants (gene flow) to a greater extent. This association between craniometric data and underlying neutral genetic variation is useful because it allows archaeologists to utilize craniometric data in cases where genetic data are unavailable or unattainable. Therefore, craniometric data can be used to test specific hypotheses (see HYPOTHESIS TESTING) about the factors that might be responsible for particular biodistance patterns, such as the influence of external migration into a population, the impact of cultural contact and exchange between populations, as well as reconstructing the past population history of a sample of archaeological sites spread across time and space. Such hypotheses are often tested by correlating (see REGRESSION AND CORRELATION ANALYSIS) craniometric biodistance matrices against distance matrices that reflect these hypothetical phenomena such as geographic as well as temporal distance, cultural group affinity patterns, or matrices reflecting specific dispersal events.

SEE ALSO: Archaeological Record; Empiricism; Evolutionary Theories; Imaging in Human Remains; Inferential Statistics; Philosophy of Science

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Cross-Sectional Geometry

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Cross-sectional properties (CSP) describe the distribution of cortical bone on any two-dimensional section through the shaft. CSP have been widely employed to make functional inferences about the predominant directions or magnitudes of loading experienced by limb bones and mandibles of humans, hominins, and other vertebrates, and to infer behavioral differences between human populations (Ruff, Holt, and Trinkaus 2006).

If a bone can reasonably be modeled as a structural beam (where length is much greater than width), CSP may reflect the bone's ability to resist mechanical loads. Cortical area (CA) reflects structural resistance to compressive or tensile loads. Second moments of area ($I = \int x^2 dA$, where x is the distance to a neutral axis of bending (NA) and dA is a unit of area) describes stiffness or resistance to bending about the NA (Figure 1a). Polar moments of area ($J = \int r^2 dA$) describe bone distribution around a longitudinal axis and reflect torsional rigidity. Section moduli ($Z = I/r$, where r is the radius in the direction of bending) reflect strength in bending or torsion (Wainright et al. 1976). CSPs are often highly correlated with bone length and body mass (Polk et al. 2000).

During animals' juvenile growth periods, bone responds to mechanical stimulation, and individuals experiencing greater loads demonstrate greater subperiosteal bone apposition than individuals experiencing less mechanical stimulation (Lieberman et al. 2003). When growth ceases, subperiosteal apposition becomes negligible, changes in CSP occur more slowly, and endosteal resorption may play a larger role in altering CSP (Ruff et al. 2006).

Functional interpretations of CSP are dependent on many assumptions and should be approached with caution. The primary assumption is that the distribution of cortical bone directly reflects the history of mechanical

loading. In this simplistic view, the processes of bone formation and resorption are assumed to provide maximum structural reinforcement with a minimum of bone material, with bone being deposited in areas that experience the highest strains. While mechanical loading clearly has an important effect on bone morphology, and strain does influence bone's response, the question of which strains (e.g., magnitude versus frequency versus rate) are most influential remains open. *In vivo* bone strain experiments have demonstrated that bones are not habitually loaded in directions that develop greatest structural reinforcement (Demes et al. 2001; Lieberman, Polk, and Demes 2004; Figure 1b), and bone is not deposited preferentially in areas that experience the highest or lowest strains. CSP are likely affected by a broad range of stimuli that bone cells experience in daily functional activities, and any simple functional interpretations of bone CSP—particularly the directionality of historically applied loads—are likely to be incorrect.

A second assumption derives from how CSP are calculated for extinct species (or any element for which *in vivo* strain data are not available). Without strain data, I and J are calculated from NA assumed to pass through the center of the bone cross-section. This assumption is false in theory and experiment (Figure 1b). Since most bones are loaded in some combination of bending and compression, the NA will be shifted toward the side of the bone that is experiencing tension. The amount of NA displacement is dependent on the ratio of compression to bending, and without strain data this amount cannot be known. Furthermore, the position of the NA is not stable during bone loading and may rotate substantially during loading cycles. Assuming that NA passes through the center of the cross-section results in errors exceeding 50 percent (Demes et al. 2001; Lieberman et al. 2004).

Some approaches to interpreting CSP are more reliable. For example, CA are not calculated using NA, and are not subject to the errors inherent in I , J , or Z . However, because bones are not loaded in pure compression or tension, the extent

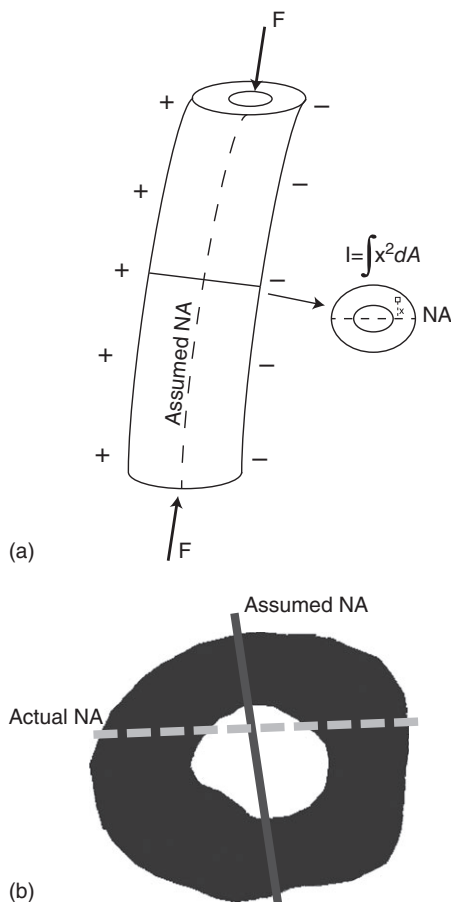


Figure 1 (a) Model of a curved, cylindrical beam subjected to axial loading (F) that generates bending strains with tension (+) and compression on opposite surfaces (-), with an assumed midline neutral axis (NA) that experiences neither tension nor compression. Resistance to bending moments is proportional to I . (b) Cross-section of a sheep tibia with the experimentally determined NA at midstance (dashed line) compared to position of NA assumed to pass through the area centroid and which gives the maximum value for I . Assumed and actual NA differ dramatically and result in very different estimates of CSP.

Source: Reproduced from Lieberman, Polk, and Demes 2004, with permission of Wiley.

of functional inferences from CA is limited. Second, when CSP are compared among bony elements from groups that have similar loading patterns (e.g., among human groups), the relative differences in CSP can be informative.

While CSP have been widely interpreted to indicate biomechanical and functional differences between individuals and species, these interpretations should be treated with caution. Bone morphology is not determined solely by functional demands related to mechanical competence. Other factors such as diet, hormonal status, marrow storage, reproduction, and mineral storage all play roles in determining diaphyseal properties and shape (Turner 2001; Ruff et al. 2006).

SEE ALSO: Human Growth and Development; Human Skeletal Data Quantification; Musculoskeletal Stress Markers; Paleopathology

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Degenerative Joint Disease

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Degenerative joint disease (DJD), also called osteoarthritis or osteoarthrosis, is a chronic, progressive deterioration of moveable joints. It is ubiquitous in both past and present populations, but past and modern populations differ greatly in which joints are affected and in DJD rates. For example, DJD of the knee, which is pervasive in present populations, was rare among ancient populations, but elbows, which are not usually afflicted with DJD in modern groups, were commonly affected in the past. Furthermore, ancient arctic populations have extremely high DJD rates, often attributed to the physically demanding lifestyle that would have been required of these peoples. However, climate has been shown to affect DJD frequency and severity (Kalichman et al. 2011).

To record DJD, osteologists look at joints for porosity (small holes), eburnation (a shiny polish caused by bone-on-bone rubbing after cartilage erosion), and osteophytes (excess bone growth), which can lead to a bony lip around the joint that may eventually lead to joint fusion. All three of these bony features can be seen in Figure 1. Medical researchers diagnose DJD through X-ray evidence of joint space narrowing and cartilage tears and hardening. Both archaeological and medical researchers identify DJD through the appearance of osteophytes. Not all osteologists agree that porosity and osteophytes are conclusive indicators of DJD; thus, some researchers suggest that only eburnation should be used as a DJD indicator. An accepted practice is to record DJD as being present on a skeletal individual if there are osteophytes and porosity present on a joint, whereas eburnation alone can be recorded as confirming an occurrence of DJD. Eburnation, the least common of the three features, is a good indicator of severe DJD.

Osteophytes have not been viewed as favorable DJD indicators because of their high correlation with age (Weiss and Jurmain 2007). Vertebral DJD, for instance, is mostly marked by osteophytes, and vertebral DJD is also strongly correlated with age. Yet, eburnation and porosity also correlate with age. Thus, age is the best predictor of who experienced DJD. The reason for the strong association between age and DJD is not well understood. The age effect may be in large part due to wear-and-tear on joints, especially if daily activities were strenuous and started early in life. Although age increases DJD in nearly all populations, researchers of past populations also report that DJD started earlier in life than in contemporary populations. This difference has led some bioarchaeologists to question whether the high heritability of DJD found in research on modern populations, mainly revealed through twin studies, may not apply to past populations. The strenuous lives of past peoples may override the weight of genes' impact. Further, medical researchers suggest that early-onset DJD is likely related to activities; for instance, former youth athletes have higher rates of DJD compared to nonathletic individuals. Nevertheless, age controls are essential when examining DJD; unfortunately, osteological adult age estimates are imprecise (see ESTIMATING ADULT AGE: AURICULAR SURFACE MORPHOLOGY; ESTIMATING ADULT AGE: PUBIC MORPHOLOGY; and ESTIMATING ADULT AGE: TRANSITION ANALYSIS).

While DJD etiology is acknowledged to be multifactorial, most bioarchaeologists who study DJD, like those studying musculoskeletal stress markers (see MUSCULOSKELETAL STRESS MARKERS) and cross-sectional geometry (see CROSS-SECTIONAL GEOMETRY), do so to reconstruct activity patterns. Questions regarding sexual division of labor, workload differences dependent on subsistence patterns, and class differences in occupations have all been addressed using DJD. DJD became used as an activity reconstruction marker after pioneering work in the 1960s and 1970s by J. Lawrence Angel, Calvin Wells, and David J. Ortner, all of whom focused

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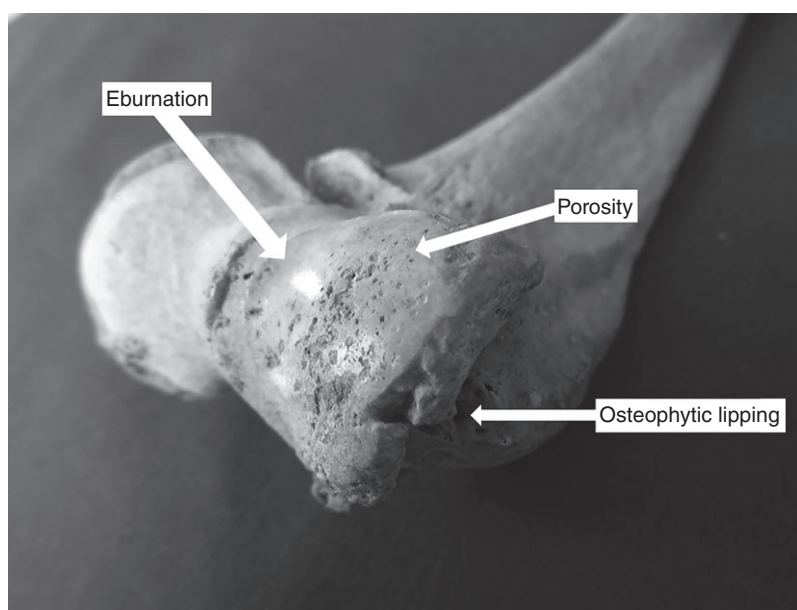


Figure 1 Evidence of DJD on an adult male's distal humerus from a California hunter-gatherer site. Porosity, eburnation, and osteophytes in the form of lipping are visible.
Source: Photograph taken by Elizabeth Weiss.

the discussion of DJD around activities and used artifacts to help support their conclusions. Anthropologists further support their assumption that activity is the main cause of DJD by citing studies on living populations that report significant correlations between DJD and specific activities or occupations (Weiss and Jurmain 2007).

Sometimes differentiating the activity causes of DJD from other factors can be difficult. For instance, individuals who engaged in physically demanding activities may be prone to trauma (see TRAUMA), which can result in localized DJD later in life. Similarly, high rates of DJD among farmers may relate to zoonotic (animal-borne) infectious diseases (see INFECTIOUS DISEASE). Certain infectious agents, such as those that cause Lyme disease, are known to cause DJD. In modern populations, obesity has been associated with an increase in DJD, which was thought to be related to the mechanical stresses affecting weight-bearing joints, but obese individuals also have higher DJD rates in non-weight-bearing joints. The body's inflammatory response has been suggested as the culprit behind the DJD and obesity link. Furthermore, DJD often afflicts

multiple joints in a single individual, which implies that DJD is systemic. The systemic cause may relate to bone turnover, which could explain why some researchers find that individuals with DJD are less likely to have osteoporosis (Weiss 2015).

The high frequency of DJD in archaeological collections makes it impossible to ignore. Future researchers may wish to examine DJD from multiple perspectives. Looking into past and present trends may help anthropologists determine the types of DJD that can be used for activity reconstructions. Conversely, using DJD for age estimation may be an attainable goal when looking at universal trends.

SEE ALSO: Bioarchaeology; Osteology; Paleopathology

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Dental Decoration

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Decoration of the teeth has constituted a widespread form of body modification, which has been documented globally. The methods of culturally enhancing teeth range from temporary or semipermanent dental works (painting, discoloration, cauterization, applications, and prosthesis) to permanent removal or modification of single teeth and sets of teeth (Alt and Pichler 1998; Dembo and Imbelloni 1938; Milner and Larsen 1991). This entry focuses on the latter. Permanent dental reduction counts as an artificial corporeal modification, defined anthropologically as the procedures on the human body that are carried out with the purpose of modifying its external aspect (Alt and Pichler 1998). Although this definition does not include and often explicitly excludes external adornments, these body ornaments cannot be conceived as a separate entity. Namely, tooth contouring would often be complemented or highlighted by external facial adornments. In this same logic, dental drillings of anterior teeth cannot be understood properly if not conceived in the context of the amalgams or inlaid stones that these dental voids would hold.

When intended for adornment, permanent dental alterations appear typically on the visible segment of the dental arch. Across the globe, these works have been accomplished with different techniques, such as ablation (tooth extraction), flat abrasion by filing, cutting, chipping, engraving, drilling, and incrustation. The host of dental decorations, and the added and inlaid materials that have been documented in traditional societies demonstrate the diversity of regional and local custom. Practiced mostly on adolescents and young adults, the initial interventions were often followed by subsequent maintenance, especially once tooth wear and decay set in or if oral complications occurred.

Distribution

Permanent dental decorations constitute an important means of cultural embodiment (Milner and Larsen 1991). This includes northern Africa and prehistoric Europe, where intentional modification appears in several Neolithic teeth from Matadepera, Barcelona. The remains of several Danish Vikings display deep horizontal grooves on their front teeth. Tooth evulsion (extraction) appears to be very ancient, as noted among North African skulls dated to the Mesolithic, although the dating of these remains is uncertain (Tiesler 2000).

Permanent dental modifications were customary also in areas of Australia, Polynesia, and Asia, namely in Bali, Pakistan, the Malayan Archipelago (Java, Sumatra, Celebes, Borneo, Philippines), Vietnam, China, Japan, and Taiwan. On the African continent, dental modification has been documented in ancient Egypt, Nubia, and large segments of sub-Saharan West Africa and the Congo. In Africa, dental extraction, filing, fracturing, and chiseling were (and in some areas still are) the preferred techniques to obtain the desired tooth contours. Beginning in the Middle Ages, some dental practices spread out of Africa, especially during the Muslim invasion in Spain and the European occupation of the Americas. Such traditional dentistry is seen in African-born individuals who had been introduced to the Americas as slaves. These African-derived dental works provide important clues to trace the geographic provenience and group affiliation of some historic African-American populations (Handler, Corruccini, and Mutaw 1982).

In the post-conquest Americas, African tooth modifications sometimes blended with dentistry practiced among Mesoamerican societies at the onset of colonization and which included grooving teeth or filing teeth to a point (Romero 1958; Tiesler 2000). In the millennium prior to European conquest, the dental modifications found in the Americas were more varied. During the Classic period (250–900 CE), the dental

modification repertoire of Veracruz, Oaxaca, and the Maya area of Central America included sophisticated forms of single and multiple drillings, which held cemented semiprecious stones or colorful fillings (Romero 1958; Tiesler 2000). To our present knowledge, all Mesoamerican tooth decorations appear to have been accomplished by way of filing, scraping, and drilling. Inlays held differently colored pastes or cemented stones, including stone incrustations crafted into the form of flat or protruding plugs. Further south, in Ecuador (Esmeraldas), metal squares were fitted into horizontal notches, while the teeth of ancient Peruvians and Argentinians were contoured into different shapes. North of Mesoamerica, filings were customary among North American tribal nations in what is now Arizona, Illinois, Tennessee, Georgia, and Texas (Milner and Larsen 1991).

Forms and techniques

The permanent dentition was clearly the target of traditional dental modification. Adult dentine is 3–4 on the Mohs hardness scale (similar in hardness to platinum), while enamel is even harder (5 on the Mohs hardness scale, harder than steel and as hard as obsidian). Modifying teeth is similar in many ways to stone and shell crafting. Either hard abrasive stones or blends of volcanic ash and/or abrasive sand are needed to manually wear down dental tissues.

Cross-culturally, filing was and still is the most common traditional method used to modify tooth shape. Filing involves the gradual and selective attrition of the tooth surface until the desired form is achieved. The exposed and abraded dental surfaces would sometimes receive a finishing polish. Similar to flat abrasion is the procedure of cutting or carving teeth with abrasive cords, sharpened stones, or metal knives. The latter commonly leave notches or narrow grooves on the anterior tooth surfaces or their incisal edges.

An alternative form to gradual dental decoration is complete or selective tooth fracture. Indirect percussion (chiseling) has been documented in traditional African and African-American dental works (Milner and Larsen 1991). These

precision blows were typically directed to the occlusal edges of anterior teeth. Tooth fractures were achieved by a single blow with a hammer or by gradually flaking off dental edges with small chisels.

Much more complex and prolonged than polishing, filing, engraving, or percussion were the procedures involved in preparing dental inlays. In the case of the ancient Maya or the Zapotecs, these were carried out in sequential operations before the final product was obtained (Fastlicht and Romero 1976; Tiesler, Cucina, and Ramírez-Salomón 2017). After an initial notch centered on the labial tooth surface was created, precision drilling was performed to penetrate the enamel and part of the dentine. Drilling was likely performed with chert tools, assisted by abrasive sands. The unfinished dental pit was worked further until its bottom was flat and its walls roughly perpendicular to the outer dental surface. Dental drilling usually penetrated into the dentine layer and could in rare occasions also collapse into the pulp chamber, causing health consequences to the person who underwent the procedure. When created successfully, the dental cavity was filled with colorful pastes or a previously fitted, barrel-shaped piece of jadeite, pyrite, or turquoise. The semiprecious stones were sealed into the opening with a calcite-based cementing material. Most of the dark inlays, identified either as pyrite or hematite, show a mirror-like surface in the Maya area, whereas green jadeite inlays would typically protrude over the dental surface as domes. The drilled dentitions of some pre-Hispanic Maya, such as a number of Classic-period settlers of the Copan Valley in Honduras, received round mushroom-like plugs. Their stem firmly anchored in the tooth cavity, these stones were topped with a much larger flat disc that would appear as large, colorful circles in the open mouth of their carriers (Fastlicht and Romero 1976; Romero 1958; Tiesler 2000). Many operations concluded with polishes achieved by rubbing the anterior teeth systematically with pastes of volcanic particles or any other polishing matter sufficiently fine and hard to act on enamel and dentine. Apart from the exposed dental plane, dental burnishes could sometimes extend over the entire anterior surfaces, producing a shiny smile.

Health risks and motivations

Despite the high success rates that the literature reports of traditional dental procedures, they could sometimes lead to discomfort and health consequences during and after the initial operation. The extent of potential hazards has not been the subject of systematic scrutiny, although modern dentistry does not leave much room for doubt that the stresses exerted by changing the physiological form of the teeth must have decreased masticatory functionality and increased the rates of infectious decay and premature tooth loss.

Apart from purely orthodontic considerations, dental decorations have received attention in both popular and scientific writings. However, surprisingly little is known about the plethora of culturally sanctioned purposes and subtle meanings of dental modifications beyond simplistic ad hoc assertions, such as its practice during rites of passage and for purposes of personal embellishment. The lived experiences attached to dental modifications are much more complex and multilayered, of course, as they unfold a host of culturally aligned motivations that range from symbolic identification, markings of identity, personal choice, and therapeutic measures. These in turn warrant a closer scrutiny of the underlying ideological aspects, including body and gender concepts, ritual choreographies and social structure, even culturally sanctioned esthetics and concepts of beauty.

In their customary dimension, dental alterations are commonly associated with puberty rites or rites of passage, which are gender distinctive in some societies. In some societies, dental modification may relate to prevention and punishment. In either connotation, the endurance of pain could be an integral or even desired part of the dental modification procedure. Also, more mundane motives are cited, such as nourishment, reproductive fitness, or curing. Modified dentitions constitute a powerful space of physical embodiment that epitomizes social identities. The public display of these dental makeovers holds meanings for each individual with modified teeth.

Methods of studying dental decoration from the archaeological record

Descriptive case studies of ancient dental work still prevail over systematic coverage. Standard taxonomies commonly distinguish techniques or instruments; others classify the artificial shapes of teeth and dentitions. Most of these taxonomies have been elaborated for specific cultural spheres. Among the latter, the elaborate nomenclatures by Rubín de la Borbolla and especially by Javier Romero (1958; Fastlicht and Romero 1976) have been continually used by scholarship. Both are geared towards Mesoamerican and in general the American continent. Romero's table distinguishes seven groups of dental reductions according to contour and surface treatment. Its use over the last decades has promoted a more systematic coverage of culturally defined patterns of tooth work in the Americas and beyond.

The culturally induced nature of this body practice allows scholars to contextualize the technical and physiopathological characteristics of dental works according to mortuary associations, cultural landscapes, and temporal trends of dental modifications in skeletal populations. Conventional odontological studies of dental decoration have been increasingly complemented with 3D surface modeling, optical microscopy, dental radiography, X-ray tomography, and scanning electron microscopic analyses that provide ever more detailed information about the methods and sequence by which teeth were modified.

SEE ALSO: Bioarchaeology; Cranial Shaping; Dental Development; Embodiment; Optical Microscopy; Oral Health; Trauma; X-Ray Radiography; X-Ray Tomography

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Dental Development

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The process of dental development (odontogenesis) begins in utero and continues until the closure of the apex (tip of the root) of the permanent third molar at roughly the end of adolescence or the beginning of early adulthood. Teeth develop and erupt in a predictable sequence, which allows for estimations of subadult age (see ESTIMATING SUBADULT AGE: DENTAL DEVELOPMENT AND ERUPTION). As teeth are not subject to plastic changes throughout one's life (unlike bone), they can serve as a record of embryological development through late adolescence. Therefore, studies of the dentition can address various hypotheses in archaeological contexts regarding growth and development; life history; and childhood diet, mobility, stress, and pathological conditions. An understanding of how teeth develop is salient to not only pursuing these research questions, but also other bioarchaeological studies of the teeth (e.g., those involving dental metrics and morphology).

Teeth are composed of a crown and a root. The outer crown is made of enamel—a hard acellular tissue that is almost entirely inorganic. After formation, maturation, and eruption, the enamel-forming cells (ameloblasts) are lost and enamel cannot be reformed. The inner portion of the tooth is composed of dentine that extends through the crown and root. Dentine forms the bulk of the tooth; it is roughly 70 percent inorganic and is not as hard as enamel. The root is then covered with cementum, a bone-like layer of connective tissue that serves to anchor the periodontal ligaments that hold the tooth in place. Unlike enamel, dentine and cementum can be created after initial dental development (via odontoblasts and cementoblasts, respectively). Nerves and vessels enter the tooth via the apex of the root to populate the pulp cavity (Figure 1).

During dental development, dentine is laid down first, enamel second (over the forming

dentine), and the root and cementum are formed last. Formation of these tissues begins at the tip of dentine (i.e., dentine horn) in the area that will become the future cusp. Development then progresses down the tooth towards the roots. Enamel formation ceases once the crown is complete, dentine formation continues to the root apex, and cementum formation follows that of the root. This process of odontogenesis is recorded in the histological structures of the teeth, which can be seen in cross-section. As ameloblasts move from the dentin–enamel junction to the outer crown, they create enamel rods (or prisms). Within these rods, there is evidence of short- and long-period increments of development. The short-period increments manifest as cross-striations and represent approximately 24 hours of growth. Long-period increments occur around every eight or nine days when development slows. This slowing manifests as dark bands, called the striae of Retzius. These striae outcrop on the surface of the enamel as transverse ridges called perikymata (see Figure 1). Each perikyma is representative of approximately eight to nine days of growth, which can be verified through an analysis of the cross-striations (Nanci 2003).

Early on, dental development is largely independent of sex; however, at later stages (into adolescence), females begin to develop teeth ahead of males. Around the seventh week of gestation, both the maxillary and mandibular deciduous incisors and canines begin to develop. The deciduous enamel crowns are almost completely developed by the first year. During the sixth month in utero, the maxillary and mandibular permanent incisors and canines begin to develop. The enamel crowns of permanent teeth are generally complete by eight years of age, with the third molar crown reaching completion between 12 and 16 years of age. Root formation continues beyond enamel development, with all roots of deciduous teeth being completed between approximately 18 months and three years, and roots of permanent teeth completing between nine and 16 years, with third molar root completion between 18 and 25 years of age (Schuurs 2012). It is important

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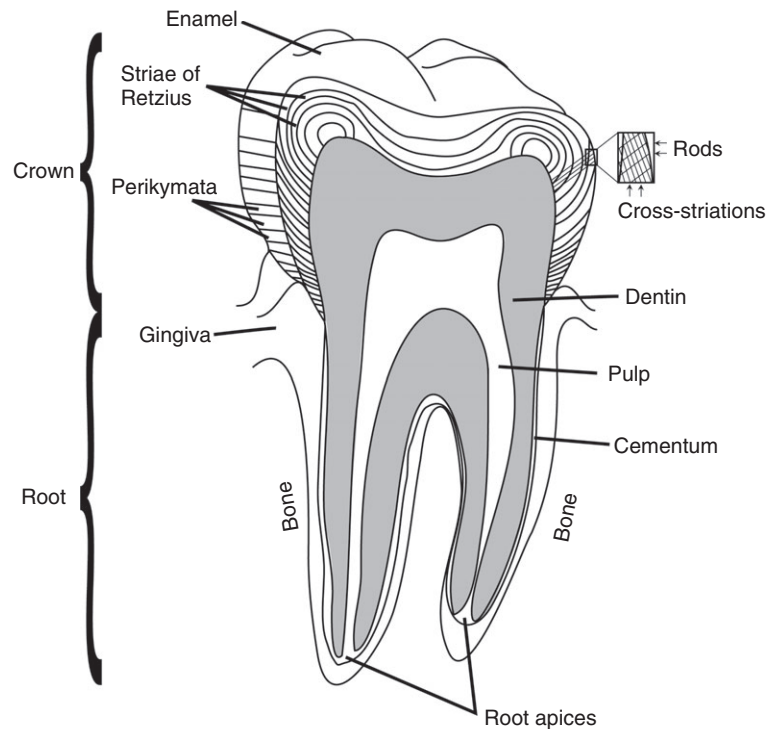


Figure 1 Cross-section of a typical lower molar illustrating the macro- and microstructures of the teeth.

to point out that crown and root development is related to, but separate from, dental eruption (see ESTIMATING SUBADULT AGE: DENTAL DEVELOPMENT AND ERUPTION). Eruption is the process of tooth migration through the bony structure of the jaws to a final position of occlusion, whereas dental development is the process of tooth formation.

The development and differentiation of teeth into different types, or tooth classes (e.g., incisors, canines, premolars, and molars), is a complex process. Historically, there have been two main theories surrounding this procedure (i.e., dental patterning): the field and clone theories. The field theory posits that each tooth type develops correctly due to a “field” effect surrounding the teeth produced by various signals. A. A. Dahlberg (1945) further added that the more mesial tooth (i.e., towards the midline) in each class would be under the strongest influence of the “field” and would therefore develop first and be the least variable. These more stable mesial teeth are called the “key” or “polar” teeth (with the exception of the lower lateral incisor, which is the key tooth

as it shows less variation than the lower central incisor). Alternatively, the clone theory suggests that each tooth class is formed by cloning cells from the location of the first tooth. As the cloning process moves distally, the teeth become more variable.

More recent genetic research has shown that homeobox genes in neural crest cells (special cells that arise from embryonic ectoderm) are largely responsible for directing odontogenesis during embryological development. Further, the signaling molecule ectodysplasin has been found to play a role in determining dental field size, which can be involved in the presence of supernumerary or missing teeth. This understanding of genetic development has been combined with the field and clone theories to advance a model termed the “cooperative genetic interaction.” In this synthesis, the roles of homeobox genes, signaling molecules, and neural crest-derived cells are acknowledged as contributing to development and tooth differentiation (Mitsiadis and Smith 2006). These three factors can be used to explain cloning (via cell division) and morphogenetic

fields or signals (homeobox genes and signaling molecules).

Dental development can also play a role in crown trait expression (see DISCRETE TRAITS). Formation of the hard tissues of the crown (i.e., enamel and dentine) is triggered through chemical signaling centers called enamel knots (Nanci 2003). Single-cusped teeth (i.e., incisors and canines) possess only a primary enamel knot, whereas multicusped teeth (i.e., premolars and molars) form secondary enamel knots during odontogenesis. These secondary enamel knots release proteins that act as both activators and inhibitors. Activation proteins trigger ameloblasts and odontoblasts to begin hard tissue production, while inhibition proteins prevent subsequent secondary enamel knots from forming nearby. A larger inhibition field produced by a secondary enamel knot will increase the amount of space between cusps. Additionally, if secondary enamel knot formation is delayed, the subsequent cusp will be shorter in relation to the previous cusp. This patterning cascade model of cusp formation suggests that the genetic code for the formation of a secondary enamel knot is repeated during odontogenesis. As the code repeats, variation accumulates, resulting in later developing cusps becoming more variable (Jernvall and Jung 2000).

Several research questions can be pursued based on this knowledge of dental development. For example, among primates, life-history traits track with these developmental processes, including weaning, the end of adolescence, and overall lifespan. Additionally, the development and eruption of teeth has been linked to brain size in primates. Generally, as brain size increases, more energy is funneled to growing a larger brain, which results in a slowing of dental development and eruption. Therefore, research on crown formation rates among various hominin species can provide information about our evolutionary past and the emergence of these life-history traits. Studies on the microstructure of teeth of early hominins, such as australopithecines and *Homo erectus*, indicate these species had shorter formation times than are seen among anatomically modern humans (Dean et al. 2001). However, Neanderthal crown formation times seem to be in line with those of modern humans (Macchiarelli et al. 2006), thereby indicating that slowed dental

growth was a relatively recent development in human evolution.

In archaeological research, stable isotope analyses are also regularly performed on teeth. As teeth are formed early in life, their isotopic signatures can serve to answer questions surrounding childhood diet (carbon and nitrogen; see DIET AND CARBON ISOTOPES and DIET AND NITROGEN ISOTOPES) and mobility (strontium and oxygen; see MOBILITY AND OXYGEN ISOTOPES and MOBILITY AND STRONTIUM ISOTOPES). These studies can be undertaken on large sections of the dental tissues to broadly represent childhood, which can also be compared to bone (representing the last several years of life) to study diet or mobility changes throughout one's lifetime. It is also possible to analyze several smaller sections within a single tooth (or individual) to represent specific periods of development. Careful analysis of the isotopic signature of these different layers can show intra-individual changes in diet or movement across the landscape at a more fine-grained scale.

Within bioarchaeological research, the sensitivity of dental enamel development to stress episodes can serve as an indicator of physiological growth disruption. Within the internal structure of enamel, as viewed in cross-section, pronounced striae could indicate a disruption of enamel secretion. The neonatal line is a prominent line found in teeth developing at the time of birth and is thought to be related to the birth event. Additionally, other so-called pathological striae, or Wilson bands, could be indicators of growth disruption, although a clear link has not yet been found (Hillson 1996). Similar disruptions are visible in the dentine as contour lines of Owen. These accentuated lines, such as an exceptionally large striation in relation to birth and the neonatal line of the enamel, are related to periods of stress (Nanci 2003). On the surface of the crown, enamel deposition disruption can be seen as enamel hypoplasias. These enamel defects are related to nonspecific stress during development and appear as furrows (linear), pits, or plane-defects (large exposures or irregular facets). Based on what is understood about crown formation, duration of stress episodes can be estimated (based on perikymata counts), as well as age of occurrence (calculated from known formation rates). Finally, there is

evidence to suggest that tooth dimensions of the deciduous and permanent teeth can be reduced during development in cases of maternal or fetal stress. Additionally, dental asymmetry between antimeres (paired teeth on right and left sides) has been linked to physiological stress in human and animal studies (Hillson 1996).

In addition to nonspecific indicators of dental growth disruption, there exist other abnormalities of enamel formation in relation to various factors. Excessive fluoride can cause enamel defects to include opacities and hypoplastic defects. Congenital syphilis can alter crown formation of the incisors (Hutchinson's incisors) and molars (Moon's and Mulberry molars). And, very rarely, enamel defects can be inherited, as in the case of the genetic disorder amelogenesis imperfecta (Hillson 1996).

SEE ALSO: Bioarchaeology; Dental Metrics; Discrete Traits; Estimating Subadult Age: Dental Development and Eruption; Malnutrition; Oral Health

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Dental Metrics

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In biological distance studies, dental metrics are used to investigate population history and structure across global populations, among sites within an archaeological region, and even within a single community. Global studies consider differences in tooth size as well as tooth shape, which are assessed through a variety of indices derived from unidimensional measurements. The use of teeth in population studies benefits from a number of factors including the generally better preservation of teeth (relative to the rest of the skeleton), the inexpensive cost of such research, and the non-destructivity of dental measurements. Moreover, morphometric approaches remain preferable for studies of population dynamics in parts of the world where poor skeletal preservation continues to prove an obstacle for ancient DNA analyses. Tooth size and morphology are also under strong genetic control, and dental development is less affected by stress than other aspects of the skeleton. However, wear and other forms of tooth damage are obstacles to population studies based on dental measurements.

Measurements of human teeth are taken using sliding calipers with extremely fine or needle-nose tips. The most common measurements collected are the mesiodistal length of the crown, buccolingual breadth of the crown, and crown height. Most researchers follow Moorees and Reed's methodology (1964) as reprinted in the *Standards for Data Collection from Human Skeletal Remains* (Buikstra and Ubelaker 1994, 62), among other sources (Hemphill 2015). Mesiodistal length is measured either between the interproximal points of contact or as the maximum length of the tooth crown in the mesiodistal plane (the latter approach is generally preferred). Breadth is measured as the maximum width of the tooth perpendicular to the mesiodistal plane. Height is measured on the buccal surface and is taken as the distance from the occlusal edge

to the cementoenamel junction. For molars, the measurement is taken on the mesiobuccal cusp. Since tooth length and width may be affected by dental wear, some researchers prefer instead to measure tooth dimensions of the cervical region (cementoenamel junction) (Hillson, FitzGerald, and Flinn 2005), although problems have been noted with this approach (Stojanowski 2007). Cervical measurements require the use of sliding calipers specifically designed for reaching over the tooth crown unless teeth are retained in alveolar sockets. Although measurements of three-dimensional images of teeth have been employed for taxonomic analysis in paleoanthropology, this approach has thus far received little use in bioarchaeology, but may prove a fruitful avenue for future research (Hemphill 2015, 289–290).

Dental metric approaches to biological distance capitalize on a more robust body of statistical approaches relative to studies that rely on categorical data (skeletal and dental nonmetric analyses). Among the multivariate approaches to the analysis of dental metric data, the most frequently used statistic is Mahalanobis distance (D^2). This statistic is used to measure the dissimilarity of two groups (i.e., skeletal samples) based on the mean, variance, and covariance matrix of the independent variables (i.e., tooth measurements). The popularity of the D^2 statistic derives in part from the fact that it takes the intercorrelation of variables (i.e., tooth measurements) into account. D^2 analysis produces a matrix of pairwise distances among all of the skeletal samples in the study. A variety of approaches are used to better interpret the D^2 matrices, including cluster analysis and multidimensional scaling. Interpretation generally follows that skeletal samples with low-distance values represent ancient populations of common ancestry and/or ones that experienced frequent gene flow between one another relative to those with larger distance values. This approach does not, however, take into account differential population size and random sampling (i.e., genetic drift), and their potential effect on phenotypic variability among populations.

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John Relethford and John Blangero (1990) developed a model for quantitative traits to compare observed and expected heterozygosity among sampled groups as a means of reconstructing past gene flow. This model, variously known as the Relethford–Blangero approach or the *R* matrix approach, has become popular among bioarchaeologists working with metric data (*R* is the genetic relationship matrix). The model incorporates relative census size and so can model the potential effects of drift. Moreover, despite the complexity of the calculations involved, Relethford has developed software (RMET 5.0) that makes this analysis relatively straightforward and produces both genetic distance estimates and F_{ST} , a commonly used statistic for reporting among-group variation. Among studies of dental metric variability within the cemetery, there is no clear preferred statistical approach and the choice of statistic is in large part dependent on the dimension of population dynamics being investigated: kinship and cemetery structure, postmarital residence, sample aggregate phenotypic variability, temporal microchronology, and age-structured phenotypic variation. As a result of methodological innovations, there has been a notable surge in both inter- and intracemetery studies of dental metric data since the 1990s.

A variety of issues must be addressed before dental metric data from archaeological sites can be used for multivariate analysis. Tooth size is known to be influenced by sex (see below), and so researchers must either separate their data for males and females, transform their data, or assume equal proportions of males and females in the dataset. Many scholars also scale the metric data for each skeleton by the geometric mean of each individual in order to increase sensitivity to shape differences (as opposed to simply tooth size). Individual tooth rescaling and many other aspects of multivariate approaches to dental metric analysis require complete datasets (data for each variable from each individual in the analysis). Thus, researchers commonly estimate or impute missing data using methods included in available statistical software packages. Prior to any data estimation, variables and individuals with a high number of missing values are culled from the dataset. Metric variables may also be removed when they demonstrate correlation with

age-at-death, presumably due to a dental wear effect.

The most recent comprehensive research on global dental metric variability and population history demonstrates results similar to those obtained in studies of genetic and craniometric variability, including evidence for the greatest level of intraregional population variability in sub-Saharan Africa (Hanihara 2013). Larger tooth size is the ancestral condition in humans and tooth size reduction has been attributed to relaxed selective pressure for large teeth following changes in food processing techniques and other cultural practices, especially in the last 10,000 years. The largest tooth sizes have been documented in Australia, followed by Melanesia, Micronesia, sub-Saharan Africa, and Native America. The smallest tooth sizes are found among some Southeast Asian populations, the Jomon/Ainu of Japan, and Western Eurasia. East/Southeast Asia and Polynesia demonstrate intermediate tooth size.

The measurement of teeth is also used to estimate sex, although this approach is generally not widely utilized by bioarchaeologists because better methods exist (Teschler-Nicola and Prossinger 1998). Male teeth tend to be larger than those of females and most studies point towards the canine (especially the mandibular canine) as the most sexually dimorphic tooth. However, the difference in tooth size between the sexes is not marked and single measurements or indices based on single tooth measurements have had mixed success for estimating the sex of skeletons. Better results have been demonstrated for multivariate discriminant functions that include measurements from both maxillary and mandibular teeth. One of the limitations for estimating sex based on dental measurements in archaeological samples is that differences in tooth dimensions vary among populations. Thus, indices or discriminant functions for sex estimation based on dental measurements must be specific to the archaeological population under investigation.

Although variability in tooth dimensions among individuals is largely attributable to genetic factors, environmental influences can also have an effect, including poor nutrition, chronic illness, and other developmental disruptions (Larsen 2015, 26–29). In a number

of bioarchaeological studies, researchers have attributed a relatively quick diachronic reduction (or enlargement) of tooth size to a change in health status, particularly following subsistence shifts from foraging to farming. Scholars have also compared permanent tooth dimensions of individuals who died as children to those of adults to test the hypothesis that the skeletons of children represent individuals who suffered from greater physiological stress during childhood as compared to those members of society that survived into adulthood. In other studies, researchers have examined fluctuating asymmetry in tooth dimensions as a possible tool for identifying individuals and populations that suffered from poor diet and health. The results of such studies have been mixed and a useful direction of future research would be to test whether elevated evidence for asymmetry corresponds with other measures of physiological stress in human skeletons.

SEE ALSO: Bioarchaeology; Biological Distance; Chromosomal DNA; Cluster Analysis; Craniometry; Discrete Traits; DNA: Mitochondrial; Estimating Skeletal Sex; Metrics; Genetics: Ancient; Genomics: Ancient

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Diagenesis of Bone

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Bone is perhaps the single greatest potential data source for archaeological and paleontological information. Skeletons are composed of an organic-mineral composite material that carries macro-, micro-, and nanoanalytical scale behavioral information. Different skeletal elements contain variable proportions of organic and mineral matrices. Bone, enamel, and dentin/ivory all contain bioapatite, a mineral similar to hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$), within a fibrous protein matrix (comprising 90% of organic content), composed primarily of collagen (see DENTAL DEVELOPMENT and HUMAN GROWTH AND DEVELOPMENT). The mineral type, microstructure, crystal size, mineral lattice tightness, and purity of bioapatite vary based on the skeletal element and individual life history. Differences in formation processes, chemistry, and structure allow for the incorporation of minor and trace elements into lattice flaws, and ionic substitutions within the mineral matrix (see DIET AND TRACE ELEMENTS). Histories of health and diet are integrated into bones and teeth via stable isotopes and trace elements (see DIET AND CARBON ISOTOPES; DIET AND NITROGEN ISOTOPES; and DIET AND SULFUR ISOTOPES), as are provenance and mobility through geochemical tracers (see HUMAN SKELETAL GEOCHEMISTRY; MOBILITY AND LEAD ISOTOPES; MOBILITY AND OXYGEN ISOTOPES; and MOBILITY AND STRONTIUM ISOTOPES), geologic age (see URANIUM-SERIES), and environmental conditions (see ENVIRONMENTAL ARCHAEOLOGY; GEOARCHAEOLOGY; and MICROARCHAEOLOGY). In order to accurately reconstruct biological, behavioral, or environmental paleo-records, skeletal materials must either be an intact record of events during life or have undergone known physical and chemical

processes that can be accounted for during analysis.

Taphonomy

Taphonomy is concerned with any changes that can occur between the time of death and the recovery of a bone. There are two general categories: biostratinomy, or the effects prior to final deposition, and diagenesis, or post-depositional effects. The alterations of bone addressed by the field of biostratinomy can include, but are not limited to, digestion, trampling, exposure, butchering, defleshing, cooking, burning, and deliberate burial (Millard 2001). Many of the physical and chemical changes incurred during this stage will determine the progression of subsequent diagenetic changes. Diagenesis is a complex process that is site-specific, often localized, and not linearly related with burial time. It is controlled by different intrinsic factors of the tissue specimen, such as its size, porosity, and chemical and molecular structure, as well as by extrinsic external factors such as microbial load, temperature, humidity, hydrology, pH, and redox conditions of the burial environment but also the skeletal tissue itself. Diagenetic pathways in bone, dentin, and enamel and their organic (collagen and other structural proteins) and inorganic (bioapatite) components vary markedly because of their chemical and structural differences. Localized manifestations of different diagenetic processes will generally follow external points of entry such as physical cracks and foramina in the bone cortex.

In addressing the complex interactions involved between bone and external factors, important questions include: what is changing, how is it changing, where are changes occurring, and how will changes alter analysis and/or data recovery efforts? Diagenetic effects take place within bone tissues, in pore spaces and cavities between components, and in the surrounding sediment. Alteration of the bone is governed by the stripping or ionic substitution

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of bioapatite with other minerals. Pore spaces and trabeculae can fill with diagenetic materials that reflect changes in burial matrix and/or location through time. Bioapatite crystals in enamel are an order of magnitude larger than in bones, limiting pore spaces and diagenetic alterations. Dentin/ivory has pore spaces akin to enamel, but organic matrices like bone prior to degradation. The burial matrix affects the outer surfaces (e.g., crusting, coating, stripping), the nature of groundwater (both its chemical make-up and transportability), and whether buried bones are crushed or deformed based on the presence/absence of diagenetic cements in the sediments. The after-effects of salt and sediment movement are more prevalent in marine contexts, but have the same considerations of exposure, physical changes, and solubility potentials.

Diagenesis to the organic phase of bone

Diagenetic changes can be broadly identified as organic, inorganic, and microbial processes. Organic diagenesis involves the decay/loss of protein (e.g., collagen, osteocalcin). Any attempt at radiocarbon dating, aDNA, amino acid racemization dating, or lipid survival will inevitably entail assessment of organic diagenesis. The stability of bones lies in the link between interwoven protein fibers, reinforced by crystalline matrices that form along the fibers. The degradation of the organic phase by microorganisms leaves the inorganic phase susceptible to chemical degradation. Recovering collagen and other proteins from archaeological samples is not difficult; the problem is determining what is left and what useful information it contains. The decomposition history of extractable proteins demonstrates that the biggest source of diagenetic effects is humic substances (complex acids formed from decomposing organic matter) moving from soil to bone during burial, where these substances can chemically link to collagen, affecting its isotopic composition. Experimental studies (van Klinken and Hedges 1992) found that humic acids react rapidly with collagen and that some standard chemical treatments do not entirely remove them, leaving changes that alter collagen to the extent of providing unreliable

isotopic measurements that can only be detected by a combination of measurements (i.e., C/N ratio, amino acid composition, and infrared spectroscopy).

Collagen survival is greatly dependent upon temperature and humidity, limiting the ability to conduct archaeological science studies on bones from warm and humid burial environments (e.g., jungles) where decomposition occurs rapidly and humic substances are abundant. Proteins can escape degradation by chemical or microbial attack when physically encapsulated in networks of soluble soil organics (e.g., tanning processes, compost, and peat bogs). Survivability lies in the complex molecular structure, where the bonds that stabilize the molecule at each level must break for the protein to “unfold” and expose sites for degradation. Collagen is the dominant protein, though other proteins (e.g., osteocalcin) can bind to minerals and survive in smaller fragments for millennia. However, experimental recovery efforts have shown that once collagen is degraded, other proteins will also be too degraded to hold useful biological information.

Microbial activity, which includes fungi, bacteria, and composite mixtures of organic and inorganic molecules, begins very shortly after death, frequently taking over a body within hours. Microbial activity begins with soft tissues, but rapidly progresses to bones, modifying both organic and inorganic phases, creating histological changes within months of deposition. The first descriptions of microbial activity on mineralized tissue were published in 1864 by C. Wedl, finding 8- μm -diameter tunnels in sections of teeth exposed to untreated well water and in fossil reptile teeth; this type of tunneling was defined as Wedl or centrifugal tunneling (Jans et al. 2004).

Three other types of microbial damage (linear longitudinal, budded, and lamellate) all appear to be caused by bacteria. These types of microscopic focal destruction can be distinguished histologically by morphology (size and shape), the presence of mineralized edges along degraded microbial tunnels, and the presence of abnormally sized crystal structures (e.g., plates). Bacterial action is prevalent under most environmental conditions, though waterlogged terrestrial sites often yield very well-preserved bone, indicating that the agents of change require an aerobic environment. Microbial activity leaves

very distinct traces within the bone matrix and the changes that are discrete and visible on histological slides.

Diagenesis to the inorganic phase of bone

Diagenetic changes in the mineral phase occur due to the damage and loss of mineral through dissolution or chemical erosion. Materials are transported and recrystallize elsewhere. Precipitation of new material can occur, or the incorporation of foreign materials into existing mineral matrices through ion uptake, or diffusion, from intrusive solutions. A third process can also occur, where a combination of loss and gain leads to internal changes of the mineral matrix to a form that differs from the original bioapatite, changing its chemical composition and structure. Dissolution is the primary operator for any mineral loss in a bone, though weight loss and porosity increases can be attributed to the loss of the organic phase.

The presence of collagen ensures the stability of the mineral matrix; thus, the ultimate source of crystallinity change is in the microbial and organic diagenetic effects that affect collagen, yet the resulting changes are part of inorganic diagenesis. Once collagen is lost, charged foreign ions are likely to take up residence within pore spaces. If the original crystalline structure of the bioapatite matrix is altered, the result is generally increased crystal size or crystallinity. Crystallinity of bone is also affected by uptake of fluorine (F^-), intrusive carbonate (CO_3^{2-}), and the transformation of bioapatite into other minerals (e.g., francolite or brushite). The rate at which changes can occur within the inorganic phase is governed by the chemical reactivity of the groundwater that can penetrate bone during burial.

Mature compact bone is comprised of lamellae traversed by individual osteons (Haversian systems). Haversian systems form by cutting through preexisting bone, growing new layers around the central Haversian canal, leaving discrete onion-like layers of bone that are separated from the surrounding tissues by a thin protein membrane (cement line). This cement line prevents the passage of material between Haversian systems except via the canals linking

osteocytes (mature bone cells). Internal bone water is generally sufficient to maintain a closed chemical system that requires the diffusion of ions either in or out, through internal canals (Hedges 2002). Diffusion or the penetration of diagenetic effects is limited to solutions within these canals, and areas physically exposed by degradation. Bone matrix within older osteon layers can thus remain unchanged until the process of bone turnover ruptures/replaces the osteon itself.

Analytical methods for identifying bone diagenesis

Microanalytical techniques for mapping and in situ analyses of elemental concentrations have become increasingly important means for assessing the extent of diagenetic alteration, reconstructing the burial environment through time, identifying diagenesis-resistant portions of bones, and reconstructing archaeological behaviors (see *ARCHAEOOMETRY* and *MICROARCHAEOLOGY*). Elemental concentrations of Sr, Zn, and Br, and Sr/Ca, Ba/Ca, and Mg/Ca ratios indicate provenance and to a lesser degree diet (see *DIET AND TRACE ELEMENTS*). Diagenesis can be approached with different analytical goals in mind: study of the diagenetic processes involved; alterations and subsequent effects on analytical chemical data recovery; comparative efficacy of different analytical methods in light of suspected diagenetic alterations; or specific focus on reconstruction of changes in the burial environment through time, as evidenced by diagenetic alterations.

To characterize and quantify diagenetic processes and their influence on the structural and chemical integrity of bones and teeth many different techniques can be applied. Studying internal structures (histology) and mapping elemental distributions uses cathodoluminescence and scanning/transmission electron microscopy (SEM/TEM). Identifying elemental additions/subtractions includes isotope ratio (IR) and inductively coupled plasma (ICP) mass spectrometry, particle-induced X-ray/gamma-ray emission (PIXE/PIGE), and X-ray fluorescence (XRF). Mineralogical, molecular, structural,

and compositional changes are identifiable using Rutherford (elastic) backscattering, X-ray diffraction (XRD), Hg-intrusion porosimetry, computerized tomography (CT), or Raman and Fourier transform infrared spectroscopy.

Current research is establishing internally verifiable analytical data for diagenetic alterations within bone samples. Verification that microfocal diagenetic effects are not biasing results employs correlations between individual osteons (Scharlotta, Goriunova, and Weber 2013) and variability within bone samples. Laser ablation, microprobe, and other microsampling methods will be important in future studies as chemical variability between different skeletal elements will help to identify diagenetic process, burial histories, and biogenic behavioral data using the same analyses.

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FURTHER READINGS

Diet and Carbon Isotopes

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The element carbon has two stable isotopes, ^{13}C and ^{12}C , which are incorporated into a plant's tissues in varying amounts depending on the specific photosynthetic pathway a plant has evolved to use (C3, C4, or CAM). For chemical reactions such as photosynthesis that do not go to completion, the product will incorporate different amounts of the heavy and light isotopes compared with the original substrate due to isotopic fractionation (Fry 2006).

The most abundant isotope of carbon (>99%) in the atmosphere is ^{12}C , with ^{13}C and ^{14}C comprising less than 1%. Carbon-14 is a radioactive isotope that is useful for dating organic remains less than 60,000 years in age (known as radiocarbon dating). It is not considered further here because it does not provide information on diet. Stable carbon isotopes are measured using isotope ratio mass spectrometry (IRMS) (see MASS SPECTROMETRY (MS)) and are reported as the ratio of ^{13}C to ^{12}C compared with an international standard of known composition. Stable isotope ratios are reported in parts per 1000 difference relative to the standard, known as a per mil (‰). Once an isotope ratio is converted to a per mil value, the delta symbol (δ) is used to report the value (e.g., $\delta^{13}\text{C}$, "delta carbon-13"). The use of the per mil value is simply to convert a small value with multiple decimal places to a whole number for ease of comparison. Stable carbon isotope ratios are reported using the following equation:

$$\delta^{13}\text{C} = \frac{{}^{13}\text{C}/{}^{12}\text{C}_{\text{sample}} - {}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}}{{}^{13}\text{C}/{}^{12}\text{C}_{\text{standard}}} \times 1000(\text{‰})$$

The International Atomic Energy Agency (IAEA), and for the USA the National Institute of Standards and Technology (NIST), have

identified appropriate international reference standards to ensure accuracy and comparability in reporting stable isotope results. Precision for carbon isotopes is within 0.1‰ for most IRMS.

The carbon isotope standard is Pee Dee Belemnite (PDB), a Cretaceous Period marine fossil limestone (*Belemnitella americana*) from the Pee Dee Formation in South Carolina. PDB was chosen as a standard because it contains more ^{13}C than almost all lifeforms. Because the original PDB standard has been exhausted, it is recommended that researchers use the updated Vienna-PDB standard (VPDB), which has been calibrated to the original standard. In-house standards are also used by stable isotope laboratories to ensure accuracy and reliability of measurements. By definition, VPDB is assigned a value of 0‰. This results in negative isotope values in organisms because their tissues have less ^{13}C than the standard.

Carbon fixation is the process by which organisms convert inorganic compounds, such as carbon dioxide (CO_2), to organic compounds. Photosynthesis is a prime example of carbon fixation. Three different photosynthetic (metabolic) pathways have evolved for fixing carbon: C3 (Calvin-Benson photosynthetic pathway); C4 (Hatch-Slack photosynthetic pathway); and CAM (crassulacean acid metabolism). These different photosynthetic pathways account for isotopic variation among plants within terrestrial ecosystems. The majority of the Earth's vegetation (~95%) is composed of C3 plants such as grasses, trees, shrubs, and legumes (common sources of fruits, vegetables, beans, and grains). These plants use a 3-carbon molecule and discriminate against ^{13}C during photosynthesis. This results in $\delta^{13}\text{C}$ values that average $-26.7 \pm 2.7\text{‰}$ (Cerling, Ehleringer, and Harris 1998). C4 plants use a 4-carbon molecule and discriminate less against ^{13}C during photosynthesis compared with C3 plants. This results in higher $\delta^{13}\text{C}$ values that average $-12.5 \pm 1.1\text{‰}$ (Cerling et al. 1998). C4 plants are often tropical grasses found in hot, arid environments, and include cultigens such as

maize, millet, sorghum, amaranth, and sugarcane (representing less than 5% of Earth's vegetation). CAM plants fix carbon using both a C3- or C4-like pathway, and therefore have values that often overlap with these plant types. These include desert-adapted plants such as succulents and cacti. Finally, carbon isotope values in marine ecosystems overlap isotopically with C4 plants due to the ^{13}C -enriched sources of carbon in the ocean (e.g., dissolved bicarbonate). The carbon isotope signatures from plants and sources of marine carbon are passed into animals, including humans, with little fractionation between trophic levels ($<1\%$). Stable carbon isotopes in bones and teeth thus reflect the sources of dietary carbon.

Applications of carbon isotopes within anthropology are diverse, and generally provide complementary lines of evidence to areas such as zooarchaeology (see ZOOARCHAEOLOGY AND HUMAN DIET RECONSTRUCTION and ZOOARCHAEOLOGY AND STABLE ISOTOPES), paleoethnobotany (see PALEOETHNOBOTANY AND STABLE ISOTOPES), food residue analysis (see FOOD RESIDUE ANALYSIS), and trace element analysis (see DIET AND TRACE ELEMENTS). They have been used to reconstruct diet among both modern and earlier human societies, ancient hominins (e.g., australopithecines and Neandertals), and also living and ancient nonhuman primates. Other applications include the analysis of archaeofaunal and archaeobotanical remains to reconstruct past foodwebs and to study environmental change.

Bone is composed of both inorganic and organic components, comprising about 70% and 30% of dry bone weight, respectively. The inorganic component found in bone is a mineral known as hydroxyapatite (referred to as "bioapatite"). More than 85% of the organic component of bone represents collagen, with the remainder comprising other proteins and lipids. Because bone tissue continuously remodels throughout life, bulk carbon isotope values reflect several years of diet (ca. 5–20 years, depending on the remodeling rate of the bone sampled). Tooth dentin is also composed primarily of both collagen and hydroxyapatite, whereas enamel is nearly 100% hydroxyapatite. Isotope signatures are incorporated into these

structures at the time the tooth formed (e.g., infancy and childhood), and do not remodel during life. Carbon isotopes of bone collagen and the carbonate in bioapatite have featured prominently in the bioarchaeological literature (see BIOARCHAEOLOGY), and have focused on important topics such as agricultural transitions (e.g., introduction of maize in the eastern US), the exploitation of marine resources by coastal and island societies, and how dietary macronutrients are differentially incorporated into bone and dentinal collagen versus bone and tooth bioapatite. In conjunction with nitrogen isotopes (see DIET AND NITROGEN ISOTOPES), carbon isotopes provide a powerful tool for reconstructing paleodiet.

The 1980s were marked by debates on whether carbon isotopes of bioapatite could be used to reconstruct the diets of ancient animals, including humans. The debate centered on two issues—one dealing with postmortem preservation of bioapatite, and the other relating to the information that can be gleaned from carbon isotopes of bioapatite versus collagen. Sullivan and Krueger (1981) argued that carbon isotopes of bioapatite could be used to reconstruct diet of ancient fossilized remains that showed complete collagen degradation. This is important because the method has the potential to extend dietary analysis to skeletal material that is thousands or even millions of years old. However, Schoeninger and DeNiro (1982) argued that postmortem mineral exchange between skeletal remains and the burial environment alters isotope values, rendering them meaningless. This issue has been overcome in part by identifying appropriate treatment protocols for removing contaminants from samples, as well as the development of new methods for screening samples for postmortem alteration. The second issue has been clarified through a series of controlled animal feeding studies on rodents (Ambrose and Norr 1993; Tieszen and Fagre 1993). These studies have found that carbon isotopes of bone collagen are biased toward the sources of dietary protein (a protein routing model), whereas the carbonate in bioapatite reflects the incorporation of all dietary macronutrients, or the whole diet (i.e., carbohydrates, fats, and protein not used to synthesize collagen). These studies found that bioapatite $\delta^{13}\text{C}$ values are approximately

+9.4‰ higher than that of the whole diet, and that collagen $\delta^{13}\text{C}$ values are approximately +5.0‰ higher than the source of dietary protein. However, spacing between the collagen and dietary protein $\delta^{13}\text{C}$ varies depending on whether the source of dietary protein is *more* or *less* enriched in ^{13}C compared with the $\delta^{13}\text{C}$ of the whole diet. More recent studies of published datasets have resulted in the development of a simple carbon isotope model (Kellner and Schoeninger 2008). A more recent revised model by Froehle, Kellner, and Schoeninger (2010) uses two regression lines to define C3 versus C4/marine protein diets, as well as C3 versus C4 whole diets. Isotope data from humans and other animals can be plotted against the model to identify not only the source of dietary protein, but also the nonprotein macronutrients (i.e., carbohydrates and fats). These developments have provided exciting new avenues from which to explore dietary variation in ancient and modern animals.

A major limitation of stable isotope analysis on ancient skeletal remains is the potential for postmortem alteration of bones and teeth. Diagenesis (see **DIAGENESIS OF BONE**) refers to postmortem chemical alterations that result from the interaction of skeletal remains and groundwater and soil from the burial environment. Over time, chemical exchange can result in postmortem alterations to stable isotope values as well as trace element concentrations. This is especially problematic for poorly preserved remains from tropical regions and for partially or completely fossilized remains (e.g., ancient hominin fossils). Carbon isotope measurements on bones and teeth that are significantly altered are often unreliable. Paleoanthropologists, bioarchaeologists, and archaeologists must take great care to evaluate sample integrity and to compare data on ancient samples with modern baseline data to ensure that results are tracking the biogenic isotope signatures. Collagen sample quality indicators, such as the percent collagen yield and atomic C/N ratio, are usually effective for identifying samples affected by diagenesis. For bioapatite, Fourier transform infrared spectroscopy (FT-IR) is a common tool for identifying samples that show low carbonate content,

evidence of recrystallization, or the incorporation of other contaminants from the burial environment.

SEE ALSO: Bioarchaeology; Diagenesis of Bone; Diet and Trace Elements; Food Residue Analysis; Isotopes; Mass Spectrometry (MS); Paleoethnobotany and Stable Isotopes; Zooarchaeology and Stable Isotopes

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Diet and Nitrogen Isotopes

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Nitrogen isotopic analysis as a method of dietary assessment is now widely used in archaeology. Since the 1970s, it has been observed that individuals have a higher nitrogen isotopic ratio ($^{15}\text{N}/^{14}\text{N}$) than their diets, and that this pattern holds true for all types of mammals, birds, fish, reptiles, and insects. Thus, the technique is used to identify the trophic position of an individual within the food chain. In archaeology, particularly for the study of human diet, this has often taken the form of distinguishing whether humans are more carnivorous or herbivorous, using the nitrogen isotopic value as a proxy for the proportion of animal versus plant protein consumed.

Underlying mechanisms

Nitrogen is a key chemical element for all organisms, as it is a fundamental part of amino acids, the molecules that are the building blocks of proteins, which themselves are the primary constituents of body tissues and metabolites (bones, muscles, skin, organs, blood). For plants, nitrogen is taken up from the soil in a variety of forms, synthesized into amino acids, and then formed into proteins (Robinson 2001). For animals, the source of nitrogen is dietary protein, which can be a limiting factor in growth and tissue synthesis.

Nitrogen exists as two stable isotopes (see ISOTOPES) which have the same electronic and proton configuration, but a different number of neutrons—the common form, ^{14}N , has seven neutrons, and the much rarer ^{15}N has eight neutrons. The resulting mass difference between the

two isotopes means that chemical reactions occur at slightly different rates, which causes variations in the $^{15}\text{N}/^{14}\text{N}$ ratio (expressed as $\delta^{15}\text{N}$) between reactant and product. This isotopic effect, known as fractionation, may occur in physical, chemical, or biological processes throughout the biosphere, and results in significant differences in nitrogen isotopic ratios in different parts of the biosphere.

A wide range of observational studies have shown that consumers have higher nitrogen isotopic values than their diets, and for each step in the food chain (plant to herbivore, herbivore to carnivore, etc.) there is an approximate 3–5‰ increase in $\delta^{15}\text{N}$ value—the “trophic level enrichment” (Hedges and Reynard 2007). The underlying mechanism is as yet poorly understood, though it is likely related to amino acid transamination and extensive nitrogen cycling within the body (Schoeller 1999). Controlled studies have shown that diet is the primary influence on body nitrogen isotopic values, but environmental and physiological factors can also have an effect. The trophic level enrichment is quite variable under a range of environmental and climatic conditions (temperature, altitude, aridity), as well as being affected by physiological factors such as water stress, starvation, and growth, and diet macronutrient composition (Boecklen et al. 2011; Makarewicz and Sealy 2014). The magnitude of these influences is unknown, because the metabolic origin of the ^{15}N enrichment between diet and body is unclear. However, general trends are that stress (water stress, heat, starvation) elevates $\delta^{15}\text{N}$, whereas growth depresses $\delta^{15}\text{N}$ values. Studies have also shown that individuals are not isotopically homogeneous—that different tissues within an individual have different nitrogen isotopic values, and that different amino acids within proteins vary in their $\delta^{15}\text{N}$ values (Boecklen et al. 2011). These patterns emphasize that nitrogen metabolism within heterotrophic organisms (including animals) is complicated—a point that is frequently overlooked in the use of the technique.

What can we analyze?

In archaeology, three key sample categories are analyzed, all of which are proteinaceous tissues containing nitrogen: bulk tissues such as bone collagen or tooth dentine; serially sampled tissues, such as hair or tooth dentine; and individual amino acids from body proteins. Each tissue represents a different time-slice of an individual's diet, depending on growth period and turnover rate: bone with its slow turnover integrates long-term diet, hair provides a linear record of short- to medium-term diet, and teeth record a snapshot of childhood diet consumed during their formation period. Sequential analyses of hair can show dietary change over a timescale of months, as can the subsections of tooth dentine, though the question of temporal resolution in dentine subsections has not been fully elucidated. Individual amino acid isotopic analysis is in its early stages, but appears to show clear signals of trophic level change when comparative data from potential food resources are limited or unavailable (Makarewicz and Sealy 2014). It has the significant advantage that analysis of multiple amino acids increases the dimensionality of the data—we are not trying to reconstruct the full complexity of diet from one or two measured parameters. Sometimes, multiple tissues are combined for a full life-history approach, with different samples from the same individual analyzed to gain a finer-grained assessment of diet (e.g., childhood versus adult diet). Key in all studies of archaeological material is a consideration of diagenesis (see *DIAGENESIS OF BONE*)—to ensure that the data measured are biogenic, and not altered postmortem. Furthermore, sample preparation and analysis must be appropriate, with due reporting of the necessary information to allow an assessment by others of sample and data quality (Lee-Thorp 2008).

Interpretations

Nitrogen isotopic values in archaeological collagen, together with carbon isotopic data (see *DIET AND CARBON ISOTOPES*), provide a direct measure of the diet of an individual. When used

as a quantitative method of diet reconstruction, the technique relies on comparing the nitrogen isotopic values of the consumer to that of potential dietary resources (thus considering relative not absolute values), factoring in the expected isotopic offset between diet and body (Hedges and Reynard 2007). Unlike for carbon isotopic values, the nitrogen in our bodies can only be derived from dietary protein, so nitrogen isotopic values tell us about protein sources, and not carbohydrate or fat intake. This must be remembered as plant foods usually have lower proportions of protein than animal sources, and so will contribute proportionally less dietary protein from the same dry weight. Another caveat is that primary and secondary animal proteins are usually indistinguishable using nitrogen isotopic data (e.g., a cow's meat and milk will be isotopically similar).

Isotopic analysis can be used to great effect in paleodietary reconstruction, but there is a high likelihood that we will never be able to calculate exact percentages of foods consumed: there are too many variables. Poor comprehension about the current unknowns (e.g., metabolic underpinnings, natural variation)—as well as a lack of scientific rigor—is responsible for many of the poorly executed studies in paleodietary reconstruction (see discussions in Makarewicz and Sealy 2014). By acknowledging the constraints of the technique, and by attempting to explore and not to ignore them, we can utilize the method to its best advantage.

Interpretation of diet from nitrogen isotopic data is always best carried out in conjunction with all other available archaeological, isotopic, and chemical evidence (see *DIET AND CARBON ISOTOPES*; *DIET AND SULFUR ISOTOPES*; *DIET AND TRACE ELEMENTS*; *ZOOARCHAEOLOGY AND HUMAN DIET RECONSTRUCTION*; *PALEOETHNOBOTANY AND STABLE ISOTOPES*; *PALEOETHNOBOTANY*; and *FOOD RESIDUE ANALYSIS*). Increasingly, inferences are drawn from the data using some form of modeling, Bayesian or otherwise, in order to constrain potential interpretations (Boecklen et al. 2011; Makarewicz and Sealy 2014).

Applications

Applications of nitrogen isotopic analyses in archaeology have addressed a range of questions about human diet in the past, including dietary composition, nutritional adequacy, social and cultural habits, and practices of child-rearing (concerning pregnancy and infant feeding), as well as plant and animal husbandry.

Neanderthal specimens from Belgium and Croatia have been found to have $\delta^{15}\text{N}$ similar to contemporary large carnivores such as wolf, hyena, and cave lion, providing quantitative support for the belief, based on other archaeological evidence, that Neanderthals were efficient large-game hunters in the cold environment of Paleolithic Europe. However, the precision and resolution of this interpretation has been questioned (Lee-Thorp 2008; Schoeninger 2014).

A key application is the identification of marine foods in the diet, as they typically have much higher nitrogen isotopic values due to the longer length of marine food chains. Such analyses have been used in coastal, lake, and river settings from the Paleolithic to post-medieval times, often in conjunction with other evidence, at both bulk protein and individual amino acid levels (Lee-Thorp 2008; Schoeninger 2014). Such work has demonstrated the importance of whaling to protohistoric Thule people in the Canadian Arctic, and showed that Mesolithic humans along the northwest coast of Europe and the Jomon people of Japan were strongly dependent on fish. Fish consumption, identified by high nitrogen isotopic values of bone collagen, tallied with other evidence for status and mobility in medieval clergy at Whithorn Cathedral Priory in Scotland. Recent work on the fish remains themselves has used nitrogen isotopic data as a proxy for fish provenance, tracing the medieval cod trade across the North Sea, which correlates with isotopic evidence for increased fish consumption in Anglo-Saxon England around this time.

Although mobility is often addressed using other isotopic systems (e.g., see *MOBILITY AND LEAD ISOTOPES*; *MOBILITY AND OXYGEN ISOTOPES*; and *MOBILITY AND STRONTIUM ISOTOPES*), nitrogen isotopic evidence for dietary change has been used as a proxy for movement, both by

comparing different skeletal elements, such as in African slaves taken across the Atlantic to work on Barbadian sugar plantations, and by assessing sequential change, for instance the clear isotopic shifts along the hair shafts of Inca child sacrifices in the Andes (see references within Makarewicz and Sealy 2014).

The identification of infant feeding (see *INFANT FEEDING*) and weaning has been widely tackled across many human groups using nitrogen isotopes (following the logic that infants are effectively eating their mothers, so should be one trophic level higher), but this area is not as simple as is often assumed, frequently leading to inconclusive results (Reynard and Tuross 2015). Nutritional and physiological stress is another problem that likely causes nitrogen isotopic change, but is potentially invisible depending on samples analyzed: for instance, modern women showed a decrease in hair $\delta^{15}\text{N}$ values during pregnancy, but this was not visible in bone collagen analyses of post-medieval individuals of known parity from St Mary Spital in London. However, work on serial sections of tooth dentine has identified clear signals of both dietary and nondietary changes in Irish potato famine victims.

The agricultural practice of manuring is visible in the nitrogen isotopic values of archaeological cereal grains, since adding isotopically enriched nitrogen to soils in the form of animal manure increases the nitrogen isotopic values of plants (Styring et al. 2015). However, nitrogen can be added in other forms (such as plant-based green manures) that do not necessarily increase plant nitrogen isotopic values. Furthermore, nitrogen turnover rates in the soil can be very protracted, so soil fertilization does not necessarily have a clear nitrogen isotopic signature visible in crops. Single amino acid analyses of plants are showing some promise in this direction.

SEE ALSO: Bioarchaeology; Bones and Ivory; Dairying; Human Skeletal Geochemistry; Statistics in Archaeology; Zooarchaeology; Zooarchaeology and Stable Isotopes

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Diet and Sulfur Isotopes

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Dietary preferences and subsistence practices are socially mediated and depend upon environmental and ecological settings. Thus, the study of ancient nutritional patterns provides insight into past sociocultural processes. This has traditionally been explored using stable carbon (see DIET AND CARBON ISOTOPES) and nitrogen (see DIET AND NITROGEN ISOTOPES) isotope analysis ($\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, respectively) from archaeological tissues. The analysis of stable sulfur isotopes ($\delta^{34}\text{S}$) offers a novel method for investigating the dietary practices of past populations (Nehlich 2015). The $\delta^{34}\text{S}$ values of terrestrial and aquatic ecosystems generally differ as a result of variation in the chemical incorporation of sulfur into bio-molecules. Furthermore, sulfur availability and reactivity vary micro-regionally and influence local sulfur isotope values in the biosphere. Thus, the $\delta^{34}\text{S}$ values of archaeological bio-remains (e.g., bones, hair, teeth, nails, pottery residues, etc.) may identify the source of dietary proteins when the sulfur compositions of different ecosystems within an area are sufficiently divergent.

Principles of stable sulfur isotope analysis

In stable isotopic analysis, mass spectrometry (see MASS SPECTROMETRY (MS)) measures the ratio of the two most abundant stable isotopes in a sample against a known ratio in a standard reference material, which is reported using the

delta notation (δ) in per mil units (‰). Thus, stable sulfur isotope analysis measures the ratio of ^{32}S (95.02%) to ^{34}S (4.22%) relative to that of a standard as follows:

$$\delta^{34}\text{S}_{\text{VCDT}} = \left[\frac{(^{34}\text{S}/^{32}\text{S})_{\text{sample}}}{(^{34}\text{S}/^{32}\text{S})_{\text{standard}}} - 1 \right] \times 10^3 (\text{‰})$$

The natural standard, Cañon Diablo Troilite (CDT), is now depleted and an artificial Vienna Cañon Diablo Troilite (VCDT) scale has been established as the primary reference material for sulfur isotope analysis (Copelen and Krouse 1998).

Bioavailable sulfur in soils is derived from sulfates in groundwater, rain, atmospheric deposition, and, importantly, the underlying geology (Bern and Townsend 2008). Plants at the base of the food chain assimilate inorganic sulfates into their tissues by converting them primarily into methionine ($\text{C}_5\text{H}_{11}\text{NO}_2\text{S}$) and cysteine ($\text{C}_3\text{H}_7\text{NO}_2\text{S}$), but also minor sulfur-containing amino acids, with minimal fractionation (ca. $\pm 1.5\text{‰}$). As heterotrophic organisms, animals cannot produce methionine internally, and instead must obtain it from dietary protein with an average consumer-to-diet offset (fractionation) of $+0.5 \pm 2.4\text{‰}$ at each level of the food chain (Nehlich 2015, 6).

The concentration of biologically bound sulfurous molecules in organic tissues is highly variable, but relatively low. Both cysteine and methionine are present in human hair, whereas only methionine is present in bone collagen; thus, hair has a higher sulfur content (4.0 wt.%) relative to that of bone collagen (0.16 to 0.22 wt.%). Because organic tissues remodel over the span, they reflect the average $\delta^{34}\text{S}$ value of dietary protein consumed over specific time periods. For example, human hair grows at a faster rate than bone collagen is remodeled, and these tissues therefore reflect the average diet of the last several months and decades prior to death, respectively.

Sample preparation and analysis

The analysis of sulfur in archaeology (see *ARCHAEOLOGY*) initially focused on sampling human hair because the available techniques were complex and required large sample sizes. Improved preparation and online mass spectrometry technology now allow for routine sulfur isotope analysis of relatively small bone collagen samples (Richards, Fuller, and Hedges 2001).

Preparation of bone collagen samples for sulfur isotope analysis follows the same procedures used for stable carbon and nitrogen isotope analysis, although it has been suggested that an ultrafiltration step purifies the collagen, thus improving results (Nehlich and Richards 2009). Collagen is isolated through demineralizing in hydrochloric acid (HCl) and may then be treated with sodium hydroxide (NaOH) to remove humic contaminants prior to being gelatinized, filtered and freeze-dried. However, because relatively little sulfur is present in bone collagen, it is necessary to prepare larger samples (up to 1 g, depending on preservation) than for carbon or nitrogen isotope analysis.

Once prepared, approximately 10 mg of purified collagen is weighed into tin capsules with 1 mg of vanadium pentoxide (V_2O_5) to catalyze sample combustion. The resulting sulfur oxide (SO) and sulfur dioxide (SO_2) gases are reduced over hot copper to minimize the amount of sulfur trioxide (SO_3) produced, and are then channeled into an isotope ratio mass spectrometer (IRMS) for analysis.

Diagenesis (see *DIAGENESIS OF BONE*) chemically alters isotope values in bone collagen postmortem, causing them to no longer reflect biogenic isotope values accumulated during life. Therefore, sample integrity must be established prior to interpretation of $\delta^{34}S$ values from archaeological samples. To do so, it is also necessary to obtain carbon and nitrogen isotope data from the same samples so that the carbon, nitrogen, and sulfur contents (wt.% C, N, and S, respectively) as well as the ratios of sulfur to carbon and nitrogen (S:C and S:N, respectively) can be assessed. Samples that fall beyond acceptable parameters are considered diagenetically altered and must be removed from the dataset prior to interpretation (Nehlich and Richards 2009).

Applications of sulfur isotope analysis in archaeological research

Sulfur isotope analysis was initially employed to investigate ecological relationships in various environments (e.g., Krouse and Grinenko 1991). While its potential for addressing the limitations of carbon and nitrogen isotope analysis in archaeological studies of diet was recognized in the 1980s, the first applications of sulfur isotope analysis in archaeology were published in the 1990s.

Initial archaeological applications of sulfur isotope analysis focused on samples of human hair because it contains more sulfur-bearing amino acids than does bone collagen. The detailed study by Leach, Quinn, and Lyon (1996) demonstrated the utility of analyzing $\delta^{34}S$ values from ancient bone collagen for addressing questions of past human diets. Since then, numerous studies have examined $\delta^{34}S$ values from bone collagen in conjunction with other isotopic parameters and archaeological data to better understand past human dietary practices. This is necessary because sulfur isotope values represent dietary protein rather than the whole diet, thus making this method fundamentally interdisciplinary. Such studies have investigated the consumption of protein from different environments (marine, terrestrial, or freshwater), social dimensions of ancient diets (e.g., gendered difference in protein consumption; weaning practices), and the presence of nonlocal individuals interred at archaeological sites, as well as the ecological, economic, religious and other factors that influenced dietary preferences in the past.

The first studies to analyze sulfur isotopes in archaeological tissues were interested in identifying whether individuals consumed marine or terrestrial protein. This is possible because oceanic sulfate in marine ecosystems has a mean $\delta^{34}S$ value around +20‰ that is passed through the food chain to the consumers of marine protein. In contrast, $\delta^{34}S$ values in terrestrial and freshwater environments are much more variable (−20‰ to +20‰ and beyond, depending on the sulfur source). Importantly, elevated $\delta^{34}S$ values (i.e., >14‰) in consumer tissues were found not only to reflect a marine diet, but also a diet based on terrestrial coastal resources that adopt the isotopic composition of oceanic sulfate due to

the “sea spray effect”. This effect may extend up to 30 km inland, although this is dependent on climatic (e.g., wind direction) and topographic factors (e.g., mountains, plains, watersheds, etc.).

The differentiation of $\delta^{34}\text{S}$ values from aquatic and terrestrial diets is applicable in regions where the sulfur isotope compositions of these ecosystems are sufficiently distinct. When they are highly divergent, $\delta^{34}\text{S}$ values can more precisely identify and quantify dietary sources. Thus, baseline environmental sulfur compositions should be established using the $\delta^{34}\text{S}$ values of archaeological faunal remains. This is because, unlike with other elements (e.g., strontium (see MOBILITY AND STRONTIUM ISOTOPES) or oxygen (see MOBILITY AND OXYGEN ISOTOPES)), it is not possible to compare the $\delta^{34}\text{S}$ values of archaeological materials with those of modern ecological samples due to environmental pollution from fossil fuels.

Dietary change over the life history of an individual has also been investigated by comparing the $\delta^{34}\text{S}$ values from their bone collagen, tooth dentin, and sections of hair and nail. In general, such changes in diet have been associated with residential mobility when interpreted within specific environmental and archaeological contexts. Nonlocal individuals have also been identified when the $\delta^{34}\text{S}$ values of their tissues differ significantly from those expected in the local environment (based on either the average value of the sampled humans or that of possible food sources). Thus, stable sulfur isotope analysis complements other techniques by offering insights into dietary changes associated with migration in past populations.

Future directions for stable sulfur isotope analysis in archaeology

As the archaeological application of sulfur isotope analysis is relatively recent, there are many aspects that require further investigation. For example, within the last several years, the detailed evaluation of $\delta^{34}\text{S}$ data using advanced statistical methods has produced more comprehensive interpretations, especially when combined with conventional isotope data (e.g., $\delta^{13}\text{C}$, $\delta^{15}\text{N}$,

$\delta^{18}\text{O}$, and $^{87}\text{Sr}/^{86}\text{Sr}$). These evaluation techniques would also be beneficial in more sophisticated applications, such as the analysis of stable sulfur isotopes in individual amino acids or protein residues (see FOOD RESIDUE ANALYSIS).

However, the relatively large amount of sample required for analysis remains problematic. This is evident in several studies that assessed childhood diet by combining dentin from multiple teeth to obtain sufficient samples for stable sulfur isotope analysis. This is unfortunate, because teeth form at different ages, and combining the samples produced an averaged childhood $\delta^{34}\text{S}$ value. However, if the $\delta^{34}\text{S}$ values from samples of different teeth (which form at predictable ages) and bones (which remodel at varying rates) from the same individual could be analyzed, it would be possible to track dietary and residential changes throughout the life history of an individual in more detail.

Future research should also strive to conduct well-designed feeding studies to accurately demonstrate which components of different food sources (e.g., leaf, stem, root) are nutritionally relevant. Furthermore, the isotopic offsets between diet and the various tissues of different consumers must be securely established to produce reliable interpretations within small error margins.

Finally, there are several interpretative aspects that should be addressed in future studies. For example, animal and cereal plant proteins in the diet contribute roughly equal amounts of sulfur-containing amino acids to human tissues, whereas legumes and fruits contribute slightly less and nuts and seeds contribute slightly more (Young and Pellett 1994). Cultural practices will also influence the dietary contribution of sulfur; for example, traditional methods of processing maize with lime doubles the concentration of digestible methionine (Katz, Hediger, and Valleroy 1974), thus increasing the contribution of sulfur from this crop to the tissues of past peoples who prepared it in this manner. It is therefore important to further investigate the influence that foods with differing amounts of sulfur, and cultural practices that enhance food quality and availability of essential compounds, have on the isotopic sulfur composition of consumer tissues.

SEE ALSO: Diagenesis of Bone; Diet and Carbon Isotopes; Diet and Nitrogen Isotopes; Human Skeletal Geochemistry; Isotopes; Zooarchaeology and Stable Isotopes

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Diet and Trace Elements

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Analyses of the trace element and/or stable isotope composition of human bones and teeth (and other tissues such as skin or hair) provide the most direct means for reconstructing the ancient diet (or paleodiet) of individuals and the populations of which they are a part. All members of *Homo sapiens* share a common chemical composition of their bones and teeth, yet there are some variations in skeletal chemistry that have been found to reflect differences in geographic origins, environmental exposures to pollutants, and the production, preparation, and consumption of foods. Trace elements from one's environment are incorporated into bones and teeth as they form during life, but may also be introduced in the burial environment. Bone is predominantly comprised of an organic protein component (collagen) and an inorganic crystalline mineral component (hydroxylapatite). Dental tissues, such as dentin and cementum, also bear significant organic components, while dental enamel, the hardest tissue in the human body, is composed of 96 percent hydroxylapatite. Trace element analyses of bones and teeth have focused primarily on sampling their inorganic component. The human body contains over 80 chemical elements, with many being necessary for various functions. Trace elements are present in very low quantities, and are usually measured in parts per million (ppm), or parts per billion (ppb), yet they have been found to vary in magnitude from individual to individual, and within bodily tissues in a single individual.

History

Variation in the trace element content of human hard tissues was first used to explore ancient diets during the early 1970s and 1980s when strontium

(Sr) was put forth as a possible indicator of relative meat consumption, or trophic level position in the food chain (Brown 1973). As a divalent and positively charged 2^+ ion, with an atomic size similar to that of calcium, strontium is able to substitute into the hydroxylapatite of bones and teeth during their formation. Other divalent ions such as barium (Ba) and lead (Pb) also substitute for calcium, although with less efficiency, due to their ionic size being greater than that of calcium. Even slight differences in ionic size relative to calcium result in a process known as "biopurification," whereby non-nutrient metal ions are preferentially removed from bone and tooth reservoirs with movement up the food chain (Elias, Hirao, and Patterson 1982; Burton 2008).

Despite the early promise of using trace elements to explore paleodiets, it was quickly recognized that human remains may be chemically altered or contaminated during their time in the burial environment (Sillen 1986; Hoppe, Koch, and Furutani 2003). This "diagenesis," or postmortem alteration, is the result of tissues reacting with soils and water during the period of burial. Diagenesis may involve the loss of "biogenic" elemental signatures, or those reflecting aspects of the individual's lifetime, and/or it may result from the addition of "diagenic" signatures reflecting contamination from the burial context itself. The degree of diagenesis varies not only from individual to individual but also from bone to bone, and even within bones. As a result, significant effort has been put into developing ways to assess the degree of diagenetic change, as well as means for removing contamination. Microscopic analyses examine the structural integrity of hard tissues, looking for signs of the physically and chemically disruptive presence of fungi, roots, mineral inclusions, bacteria, and so on. Fourier transform infrared (FTIR) spectroscopy or X-ray diffraction (XRD) is used by some researchers to identify whether the mineral component of bones and teeth has undergone significant diagenetic alteration. These techniques are used to produce a crystallinity index (CI), with a normal range of nondiagenetically altered crystallinity values

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falling between 2.6 and 4.0 (Wright and Schwarcz 1996; Nielsen-Marsh and Hedges 2000). In addition, the presence of elements not typically found in uncontaminated bone, such as uranium or rare earth elements (REEs), can warn researchers that diagenetic alteration has likely occurred. A quantitative measure of the occurrence of diagenesis is possible through the measurement of a tissue's calcium/phosphorus (Ca/P) ratio. This ratio identifies the loss of the organic component in bone, and/or the addition of new minerals from the burial environment. Ca/P ratios of approximately 2.0 are considered indicative of unaltered hard tissues. If one or more of these approaches suggests that diagenesis has likely occurred, the bone or tooth samples may be chemically treated with a weak acid in order to attempt to remove diagenetic elements prior to conducting paleodietary analyses (Hoppe et al. 2003).

Not surprisingly, early studies of Sr and other trace elements, such as barium (Ba), zinc (Zn), copper (Cu), and magnesium (Mg), produced variable results, leading eventually to skepticism regarding the utility of trace elements for reconstructing paleodiets at all. This exploratory phase of trace element research demonstrated the importance of developing new models for interpreting trace element values, rather than assuming that all elements would vary simply and predictably with trophic levels (see key review publications by Buikstra et al. 1989; Ezzo 1994; Burton and Wright 1995; Burton and Price 2002; Burton 2008).

Today, researchers investigating ancient diets using trace elements take care to choose appropriate elements for analysis (those that are bone-seeking and may substitute for Ca in quantities that are measurable). They also recognize the need to develop an understanding of how elements vary in dietary components, how elements from dietary components interact within the body itself, and what factors may influence their uptake by bones and teeth (e.g., reproductive status, health, age, and the presence of other bone-seeking elements in the diet) given a particular archaeological and/or ecological context.

Key elements

The most commonly investigated trace elements for paleodietary reconstruction are Sr and Ba. Because both Sr and Ba are not required for any metabolic functions of the body, it is expected that their presence in bone and tooth tissues is only proportional to their presence in the diet during life (assuming diagenesis has been ruled out). Both of these elements are passed on from soils, to plants and hence to consumers, with discrimination against the uptake of Sr increasing with trophic level placement of the consumer (biopurification). The decrease in the Sr/Ca and Ba/Ca ratios with higher positions in the food chain has led researchers to equate low ratios with high meat consumption. This approach to investigating the degree of carnivory of consumers is, however, complicated by geological variability in soil chemistry and the fact that the research results are not consistently successful when attempting to use Sr/Ca and Ba/Ca ratios to elucidate intermediate trophic positions. Burton and Price (2002) argue that the theoretical foundation for using Sr/Ca and Ba/Ca to infer paleodiets is sound, but that simplistic interpretations equating certain values with meat consumption have proven to be misleading (Burton 2008).

Dozens of additional trace elements have been measured in bones and teeth since the first explorations of Sr variation. While some are used to reconstruct exposure to pollutants in the past, such as lead (Pb) or cadmium (Cd), the greatest focus has remained on paleodietary reconstruction—despite the fact that the ability of each element to indicate anything about past diets is often unclear. For example, because Zn is also a positively charged divalent ion, which can substitute for the Ca in bones in teeth, it has also received considerable attention by researchers interested in paleodietary reconstruction. The presence of Zn in bodily tissues has often been assumed to vary such that higher Zn/Ca ratios reflect greater meat consumption, or a higher trophic position. This assumption is based in large part on the observation that most body Zn is stored in muscle, and, as such, it might be reasonable to expect that someone who eats more muscle (meat) would demonstrate a higher Zn/Ca ratio in their own tissues. In the 1990s, it was

argued that Zn should not be used as a paleodietary indicator because, as an essential element, it is metabolically regulated in the gut (Ezzo 1994). More recent research, using dietary data collected from a living population of children in Mexico, found that Zn did vary with aspects of diet, but not with meat consumption. In this case, Zn/Ca ratios were found to vary with dietary quality (or bioavailability of Zn), rather than with any singular aspect of diet (Dolphin and Goodman 2009). Despite these complications, many researchers still erroneously use Zn as a simple paleodietary indicator based on the assumption that this element varies only by meat consumption.

Sampling and instrumentation

Sampling and analytical considerations vary depending on whether bone or tooth tissues are to be examined. The choice of tissue sample is also influenced by the nature of research questions regarding the timing of dietary shifts. Bone collagen and apatite are replenished every seven to ten years; thus the chemical signatures measured from bones reveal information about diets consumed during roughly the last decade of one's life. Each dental tissue, however, grows at a known incremental rate and does not remodel once formed. In the case of tooth enamel, the layers of incremental growth visible in deciduous and permanent crowns retain the chemical signatures of individuals' earliest years (from approximately four months in utero to 18+ years of age). When the special challenges and opportunities linked to each tissue type are accounted for, trace element analyses may then be used to comment on shifts in diet relative to changes in geographic location, socioeconomic status, or weaning.

Instruments used to analyze the trace element content of bones and dental tissues may include atomic absorption spectroscopy (AAS), atomic emission spectroscopy (AES), proton-induced X-ray emission (PIXE), neutron activation analysis (NAA), or synchrotron X-ray fluorescence (sXRF), among others. The traditional, and still most commonly employed, means of attaining trace element values involves crushing and then dissolving pieces of bone or tooth, with the resulting solution being analyzed via inductively

coupled plasma mass spectroscopy (ICP-MS). In recent years, the sensitivity of ICP-MS measurements has been combined with the precise sampling capabilities of laser ablation systems (LA-ICP-MS). These systems allow for the microsampling of bone and tooth tissues, with material removed via laser from areas as small as 20 or 5 microns producing good quality data. LA-ICP-MS and other minimally destructive techniques allow for the exploration of elemental variation within tissues (and their specific times of formation).

Future directions

Going forward, trace element analyses of human remains will likely continue to explore microspatial analyses that help to avoid complete destruction of irreplaceable samples. When combined with histological information regarding internal microstructures of tissues, these microspatial sampling strategies will continue to reveal more about the complexities of trace element incorporation, and the various factors acting upon it. Further exploration of non-traditional paleodietary indicators, such as Br (Dolphin et al. 2013), or of elemental indicators of population movements (e.g., neodymium), may expand the kinds of trace elements that researchers draw upon. The growth of interest in trace elements other than Sr, Ba, and Zn, and the combination of trace element and stable isotope analyses by several researchers, suggests that multiple means of assessing aspects of diet could produce more nuanced understandings of paleodiets in the years to come. While there will undoubtedly be further improvements of instrumentation and sampling strategies, the most important barrier that researchers will need to work to overcome is the incomplete understanding of what most trace elements actually reveal about diet, if anything. Future interpretations will need to consider inter-elemental interactions, the impact of dietary quality and micronutrient bioavailability, and the effects of reproductive status, growth, and development, and health status on variability in values. Paleodietary modeling based upon data collected from well-documented contemporary tooth

biobanks may also shed light on the complexities of using trace elements to infer past diets. Biobanking projects such as the Norwegian Mother and Child Cohort Study (MoBa) and the Avon Longitudinal Study of Parents and Children (ALSPAC), with their samples of tens of thousands of teeth, and years of longitudinal data regarding diets, activity, and health are providing insights on contemporary epidemiology, but can also be used to gain new perspectives on the appropriate engagement of trace elements when reconstructing aspects of past lives.

SEE ALSO: Bioarchaeology; Diagenesis of Bone; Diatoms; Diet and Carbon Isotopes; Infant Feeding; Zooarchaeology and Human Diet Reconstruction

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Differential Diagnosis

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Differential diagnosis is a procedure for deciding what problem a patient has through systematic comparison of diseases with overlapping signs and symptoms. The concept developed in parallel with formal diagnosis in systematics. The *Oxford English Dictionary* credits the first use in English to the 1829 translation of a French dermatology text. Modern physicians can download cell phone apps that write a differential diagnosis to fit the case at hand, and there are versions that use probabilistic models. This standard practice in medicine has been adapted by paleopathologists for use in ancient remains.

The American physician Joseph Jones (1833–96) is credited with introducing differential diagnosis to paleopathology in his 1876 Smithsonian monograph *Explorations of the Aboriginal Remains of Tennessee*. Although Jones did not use the phrase as such, his diagnosis of ancient syphilis is detailed and technologically advanced for its day. Like Jones, many of the early contributors to paleopathology were physicians who engaged in informal differential diagnosis as a matter of course. Formal presentation of the technique of differential diagnosis was slow to appear in anthropology and archaeology journals. The first appearance of the phrase in *American Antiquity* is in 1945, in an article on the misdiagnosis of congenital anomalies such as trepanation, by geneticist William M. Goldsmith. In the first use in the *American Journal of Physical Anthropology*, in 1952, archaeologist William A. Ritchie identifies tuberculosis in the New World, citing a 1946 case study by Venezuelan physician Antonio Requena that presented a differential diagnosis. Ritchie himself consulted a panel of physicians. The earliest use in *Antiquity* is in 1988: Nicholas Reynolds takes to task a sensational overinterpretation of Anglo-Saxon mortuary practices, suggesting

that differential diagnosis of rape is problematic. Surprisingly, none of these authors presents a formal differential diagnosis, and all reflect the participation of physicians in identifying diseases.

All paleopathologists do differential diagnosis, whether or not they include a formal presentation of the procedure in their written reports. Publishing one's differential diagnosis is a stylistic and rhetorical choice in science writing. Some researchers take an extremely positive approach to identifying diseases and speak or write from authority. Others prefer to show their work, addressing inferences, probabilities, and ambiguities. This choice is particularly appropriate when a study concerns subjects far removed in time and way of life. There is lively debate, particularly about diseases in fossil humans. For example, Nariokotome, the 1.5-million-year-old *Homo erectus* adolescent from Kenya, was once thought to have *scoliosis*—lateral curvature of the spine—*spondyloepiphyseal dysplasia tarda*—a dwarfism syndrome—and *spina bifida occulta*—a developmental defect of the sacrum. Careful attention to features characteristic of each of these conditions, together with a detailed differential diagnosis of syndromes affecting the spine in modern humans, shows that the supposedly pathological features identified in the earlier studies are either normal in fossil humans or normal in immature spines (Scheiss and Haeusler 2013). The Nariokotome Boy was in good health when he died, and was not abnormally short.

Disease in domestic animals is a relatively new topic that offers insight into ancient attitudes and behaviors. A multidisciplinary team including a veterinarian examined a dog burial from medieval Guimps in France. In addition to several healed and healing fractures, the dog had a curved radius caused by injury to the developing forearm and a dislocated kneecap, both subjected to differential diagnosis. Appealing to “diagnostic parsimony,” the authors attribute all the injuries to abuse (Binois et al. 2013, 44), pointing out that there has been little attention to multiple trauma in the paleopathology of animals.

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The technical difficulties of differential diagnosis deserve attention when similar diseases have overlapping signs (Blau 2005), or affect the skeleton only secondarily (Lefort and Bennike 2007). One example is a child from a kurgan in Uzbekistan with an opening in the skull at *bregma*, the intersection of the coronal and sagittal sutures. Postmortem damage, trauma, surgery, infection, and several developmental defects are explored in the differential diagnosis. A second example is a man from the Æbelholt Monastery in Denmark, a medieval leprosarium. Leprosy, treponematosi, smallpox, ergotism, rheumatoid arthritis, and sarcoidosis are included as differential diagnosis that identifies leprosy as the most probable cause of this man's bone lesions (Lefort and Bennike 2007). His medieval contemporaries were right in their diagnosis.

A problem particular to paleopathology is diseases for which conventional diagnosis depends heavily on medical history, soft tissue histology, or serology not available from ancient remains. The sacrum of an Egyptian woman from the twenty-sixth dynasty shows an unusual pattern of new bone growth and destructive lesions. A differential diagnosis including five kinds of tumors, three kinds of cysts, and several infectious diseases is sorted out using histology (Strouhal and Němečková 2004). The studies cited here appear in journals that include many excellent differential diagnoses.

The best differential diagnoses are built on a careful reading of the medical literature and organized to make the most of the limited features that can be observed in a skeleton or mummy. Formal, tabular presentation clarifies the author's logic. Systematic texts written by and for paleopathologists on joint diseases, metabolic diseases, ancient medicine, and the like aid in economical presentation of differential diagnosis. Careful studies of known-diagnosis collections and clinical records are particularly important in critical evaluation of differential diagnosis as applied to ancient remains (Santos and Roberts 2006).

Differential diagnosis depends on careful fieldwork, recovery, and curation. Archaeologists should screen around extremities and body cavities, recording in detail the location of any unusual items. Training for excavators of

human remains should include some awareness of gallstones, bladder stones, gastrointestinal tract contents, and calcified tissues relevant to ancient health. Differentiating amputation from poor recovery or death during childbirth from funeral practices can depend on good field documentation. Details of limb positions may be important in some diagnoses. Teamwork is essential, because the rapid growth of radiological, histological, and biochemical techniques that permit the differentiation of similar diseases requires interdisciplinary effort.

Some paleopathologists have stretched the phrase differential diagnosis to fit the identification of ancient diseases at a population level. If the features characteristic of a disease are present in a series of remains from a site or region—or for some researchers if they covary—that disease must have been present. Whether a given person had the disease is seen as a less-important question. This is a misuse of the medical concept, which applies to individual patients. Its use distances the language of paleopathology from that of clinical medicine in eccentric and unnecessary ways, when neologisms such as *paleoepidemiology* or *population pattern* are more accurate and less liable to misunderstanding across disciplinary lines.

Three limitations of differential diagnosis should be kept in mind. First, the late Donald Ortner of the Smithsonian Institution frequently reminded paleopathologists of the old saw “a dog may have both ticks and fleas.” The features of a given skeleton or mummy may be the result of two or more disease processes, whereas differential diagnosis attempts to fit them into a single entity. Second, many medical texts remind us that “when you hear hoof beats, you shouldn't think of zebras.” It is tempting to favor a rare condition not yet identified among ancient people when a more common condition is more likely. Third, differential diagnosis is possible only for diseases that conform to a modern clinical picture. Infectious diseases may have evolved in ways that change their features over time. Environmental conditions and life-history constraints may alter the frequency and covariation of features of ancient disease. These complications are perhaps the most interesting questions in paleopathology.

SEE ALSO: Burial Excavation; Congenital Conditions; Infectious Disease; Metabolic Disease; Oral Health; Trauma

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Discrete Traits

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Discrete traits are those characteristics of a skeleton and dentition that can vary individually or by sex, kinship, population, or species. Also called discontinuous, morphological, or non-metric traits, they are measured on a categorical or ordinal scale. These traits are heritable and believed to be selectively neutral (conferring no evolutionary advantage). As such, they are useful in estimating ancestry, kinship, biological distance (see BIOLOGICAL DISTANCE), or sex (see ESTIMATING SKELETAL SEX: CRANIAL AND PELVIC MORPHOLOGY) in bioarchaeology (see BIOARCHAEOLOGY), forensics, or paleoanthropology. While advances are being made in the use of ancient DNA to answer many of these questions, discrete traits are often a better option due to taphonomic constraints (see DNA: MITOCHONDRIAL). Most bioarchaeological discrete trait research emphasizes dental traits because teeth are well preserved in almost all archaeological contexts, while other skeletal elements and DNA will degrade more quickly over time. Discrete skeletal traits provide an advantage over metric traits because they can be scored without having complete skeletal elements.

Discrete dental traits are typically shape variations. The majority of traits are specific extra cusps or ridges, like the metaconule, a fifth cusp on the maxillary molars that can be present between the distal two cusps. Dental traits can also include position or gross morphology, such as incisors that do not sit flush in the dental row or a dramatic size reduction up to congenital absence. Cranial and skeletal nonmetric traits include variations in the growth process of bone leading to variations in foramina or additional bone features. Cranial discrete traits are often additional foramina or suture variations, such as the presence of a notch or foramen above the eye orbit or a

short suture under the orbit. Postcranial discrete traits are more varied, but often involve additional foramina or variations in the shape of articulations.

Throughout the nineteenth and early twentieth centuries, anthropologists described individual dental variation by especially focusing on single traits in single populations, like the additional Carabelli's cusp on upper molars common in modern Europeans or the taurodont molar roots of Neandertals. These single features were often used to characterize a population, although the traits are found in varying frequencies across human populations. In the early twentieth century, Aleš Hrdlička found the standardization of descriptions lacking and undertook a study of shovel-shaped incisors, of which he gave a thorough description of multiple grades of the trait when present and a comparison of the relative frequency of the trait in human populations and nonhuman primates and other mammals (Hrdlička 1920). This work began the systematic study of dental morphology and provided evidence for the biological relationships among human populations and between humans and other mammals. In the mid-twentieth century, Albert Dahlberg furthered this standardization by developing and sharing dental plaques (casts) showing three-dimensional ranked expression of several traits (Turner, Nichol, and Scott 1991). Christy Turner and colleagues updated and expanded Dahlberg's work in the Arizona State University Dental Anthropology System (ASUDAS) with further descriptions and standardized trait plaques (Turner et al. 1991; Scott and Turner 1997). With the written descriptions for recording the categorical or ordinal rank for each trait and the corresponding three-dimensional plaques, inter- and intra-observer error can be reduced within and across studies. Bailey (2002) found the modern human basis of the ASUDAS dental traits inadequate for paleoanthropological studies and described an additional 16 traits found in high frequencies in Neandertals. Despite these additions, the ASUDAS remains the standard for assessing discrete dental traits.

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Similar to discrete dental traits, anthropologists identified discrete traits throughout the rest of the skeleton and cranium as early as the eighteenth century. Some features, such as an open metopic suture, which normally closes in the first few years of life, or ossicles, small accessory bones found within the sutures of the skull, were often included in early studies of skeletal collections. However, recording practices varied substantially, ranging from a minimal categorical presence/absence to an ordinal ranking of suture closure or precise identification of the number and location of ossicles. Other studies focused only on traits present in the specific population being examined. At a seminar at the Field Museum of Natural History in Chicago in 1991, multiple experts devised standard recording practices for human skeletal remains, including nonmetric traits, leading to the publication of *Standards for Data Collection from Human Skeletal Remains* (Buikstra and Ubelaker 1994). Like the ASUDAS, this guide provides descriptions of categorical or ordinal recording procedures for improved inter- and intra-observer consistency.

In the scoring of all discrete traits, standards such as the ASUDAS and *Standards for Data Collection from Human Skeletal Remains* should be followed (Buikstra and Ubelaker 1994; Turner et al. 1991). In general, scores for all traits should be recorded, including the score of absent or unobservable. Traits should be recorded from both sides of the body, although statistical analysis may only use one side. Tests of intra-observer error should be conducted on the data to ensure repeatability of results, along with inter-observer error tests if multiple people collect the data (Buikstra and Ubelaker 1994). For ease of statistical analysis, ordinal discrete trait data are often dichotomized to a present/absent observation. This process is justified by the presumed additive genetic control of dental and other skeletal traits, and standard breakpoints for dental traits are given in the ASUDAS descriptions (Turner et al. 1991). However, this process reduces variation within and among populations, limiting the usefulness of these traits for study (Buikstra and Ubelaker 1994).

The morphological traits described by the ASUDAS and *Standards* manual are heritable and believed to be selectively neutral (conferring

no evolutionary advantage), making them useful for forensics, bioarchaeology, and paleoanthropology (Buikstra and Ubelaker 1994). Some of the early descriptions of discrete traits included family studies, but more in-depth research on heritability began in the 1950s. Working with mice, Grüneberg (1951) noticed that some discrete dental traits were more common in some lineages, and cross-bred mice to determine the genetic basis for those traits. Torgersen (1951) found a similar phenomenon in cranial sutures and ossicles while studying human radiographs. Since then, multiple studies have examined human morphological traits, comparing twins, non-twin siblings, and other family members. While the actual heritability estimates vary, there is a general consensus for high heritability controlling discrete traits throughout the skeleton and dentition (Buikstra and Ubelaker 1994; Scott and Turner 1997).

Forensic anthropologists are often called to identify individuals based on skeletal remains, with both sex and ancestry often requested, although there are serious limitations in providing this information. Sex variations are dependent on the population, and “races” are socially constructed categories that are not distinguished by consistent biological divisions between those categories. For example, the practice of hypodescent (assignment of race to match the parent with the lowest social status) prevalent in the United States allows a wide variation in the ancestry of those labeled African-American, while ancestry signaling Hispanic ethnicity can vary depending on the geographic location within the United States (Edgar and Ousley 2013). However, being hereditary, discrete traits can provide useful information as long as these factors are considered. Discrete traits in the pelvis, such as the presence of a ventral arc in females, can be useful in determining sex. Using multiple discrete dental traits together in analysis can lead to fairly confident assessment of ancestry when using a representative comparative sample (Edgar and Ousley 2013). This work builds on other cranial discrete traits identified as distinctive among those with African, European, or Asian ancestry, such as the shape of the nasal bones and nasal aperture.

Determining kinship or biological distance in bioarchaeology is also aided by the use of discrete traits. This type of study increased dramatically after several studies in the 1950s showed the high heritability of these discrete traits (Buikstra and Ubelaker 1994). Biological distance studies can range from single burials or cemeteries to large interregional comparisons. At the single burial or cemetery level, discrete traits can be compared to assess the likelihood that individuals are similar enough to be considered biologically related. This can be done using rare traits or a larger number of less-unique traits. If the individuals share multiple rare traits or if other traits are found correlated at a higher frequency as compared to similar populations, the individuals are likely to be related. This was found to be the case in the Upper Paleolithic triple burial at Dolní Věstonice in the Czech Republic where the three individuals shared multiple dental traits, as well as three traits uncommon in other Paleolithic populations (Alt et al. 1997). This kind of comparison can be expanded to examining potential kinship within a cemetery or site. Finding more variation between cemeteries than within them would indicate biological relatedness factoring into burial location. Cluster analysis can be used to determine if morphological traits correlate with geographic patterning in burials, indicating kin groups buried in specific cemeteries. Again, the analysis could be expanded further to compare multiple sites, considering migrations of people if the region does not follow an isolation-by-distance model where populations become less alike the further away they are geographically. Generally, this type of study will use a distance statistic, such as a mean measure of divergence, to test the biological distance based on nonmetric traits.

Nonmetric traits can also help identify hybridization between species or admixture between distinct populations of the same species. Trait frequencies of a descendant population will often be intermediate to the two parental populations, but can also be closer to one parent or the other. Additionally, normally isolated traits will often be passed on together, a process known as linkage disequilibrium. This can lead to increased variation in the descendant population, as found in modern Pima Native Americans, who have some European admixture. Finally, rare

or abnormal traits are more common in hybrid admixed populations, such as supernumerary teeth in many nonhuman animals (Springer 2013).

SEE ALSO: Chromosomal DNA; Dental Metrics; Human Populations; Mortuary Analysis; Osteology; Taphonomy

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DNA: Mitochondrial

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Characteristics of mitochondrial DNA

Mitochondrial DNA makes up the genome of mitochondria, the organelles in eukaryotic organisms which carry out oxidative phosphorylation, the chemical reactions by which energy is synthesized. Mitochondria are thought to be derived from an endosymbiotic prokaryote—a bacterium that may have been engulfed by another during a process known as phagocytosis, to their mutual benefit—perhaps around 2 billion years ago. Many of the genes originally located in the endosymbiont's genome were subsequently transferred to the nuclear genome (Friedman and Nunnari 2014).

Mitochondrial DNA is unusual in several respects compared to nuclear DNA. Introns (noncoding DNA) are absent, and some codons deviate from universal genetic code. The mitochondrial genome is circular and (like bacterial genomes) consists of a “heavy” (H) strand and a “light” (L) strand, where the difference in mass is due to differing proportions of (larger) purines versus (smaller) pyrimidines in their sequences (Taanman 1999). In humans, the numbering of the positions of the mitochondrial genome's 16,569 nucleotides is done with respect to a reference sequence, known as the revised Cambridge Reference Sequence (rCRS), which was the first mitochondrial genome sequence ever published in 1981 and corrected for errors in 1999 (Andrews et al. 1999). All mitochondrial lineages are identified and classified on the basis of DNA sequence differences with respect to the rCRS. Increasingly, however, a “Reconstructed Sapiens Reference Sequence,” which takes into account archaic hominin mitochondrial genomes to reconstruct an ancestral root haplogroup for humans, is being viewed as a more phylogenetically useful

reference sequence than the rCRS, which is a European lineage.

The human mitochondrial genome has some regions whose DNA is used for the production of proteins (coding regions) and some regions that are not used for protein production (non-coding regions). The noncoding portion of the mitochondrial genome that makes up nucleotide positions 16024–576 is referred to as the control region. In addition to containing the site of the origin of DNA replication (in a region known as the D-loop, or displacement loop), the control region contains two hypervariable regions (known as HVRI and HVRII: “hypervariable region I and II”) in which DNA bases mutate at more rapid rate (roughly 10-fold in humans) than the rest of the genome.

The rest of the human mitochondrial genome (np 577–16023) contains 37 genes: 28 on the heavy (H) strand and 9 on the light (L) strand. Mitochondrial genes, which do not recombine with the nuclear genome, encode proteins and RNAs involved in energy metabolism. Mutations within mitochondrial genes have been linked to a number of disorders, including energy production, neurodegenerative diseases, and cancer (Taanman 1999).

Inheritance

The mitochondrial genome of an individual is maternally inherited. Although sperm have been observed to donate mitochondria to oocytes during fertilization, they do not appear to be inherited by later generations of cells in the embryo except in extremely rare cases. The mechanism for this phenomenon, whether through active elimination or dilution of sperm-derived mitochondria, is currently unknown. This maternal inheritance, coupled with the greater abundance of mitochondrial genomes relative to nuclear genomes in each cell, the rapid rate of mutation within the hypervariable regions, and the nonrecombining nature of the genome, make mitochondrial DNA a

record of maternal genetic history. However, due to their circular structure, all the regions of a mitochondrial genome are tightly linked and inherited together. Thus, mitochondrial genomes effectively constitute only a single genetic locus or marker. They therefore reflect the evolution and migration of a small subset of the population and are much more affected by genetic drift. Thus, there are some limitations to the inferences that can be drawn from mitochondrial-based studies alone. However, due in part to its greater abundance in cells, mitochondrial DNA is much more likely to be recoverable than nuclear DNA from ancient remains. This greater likelihood of recovery, as well as relatively less computational complexity and expense, is reflected in the greater proportion of paleogenetics literature reporting mitochondrial diversity than nuclear diversity.

Identifying ancestry

In humans, mitochondrial lineages (haplotypes) related by recent shared ancestry are classified into taxa known as haplogroups. Haplogroups are named according to a system that reflects the order of their characterization, beginning in the 1990s. Haplogroups A, B, C, D, present in indigenous American and Asian populations, were the first to be identified. Haplogroups H, I, J, and K were characterized in European populations, and haplogroup L in African populations. The early mitochondrial DNA studies were low-resolution and based on analyses of the length of fragments resulting from digestion of the genome with restriction enzymes (restriction fragment length polymorphisms, or RFLPs). Refinement of phylogenetic relationships between haplogroups steadily improved as direct sequencing, first of HVR I and II and then of the noncoding portions of the genome, became increasingly common. As resolution and sampling coverage of populations increased, new genetic variation was uncovered and additional haplogroups and sub-haplogroups were added to the mitochondrial phylogenetic tree. Today the most up-to-date mtDNA tree (phyloree.org), is based on over 25,000 complete mitochondrial genomes, the highest level of resolution possible. It currently contains over 5,400 haplogroups and is revised regularly to

include new mitochondrial genetic diversity as it is identified. (van Oven and Kayser 2008)

Because the distribution of mitochondrial lineages largely reflects the genetic histories of populations, mitochondrial DNA-based studies in both ancient and contemporary populations have been used to identify significant evolutionary events in human history. For example, ancient mitochondrial DNA recovered from skeletal elements in the Denisova Cave in the Altai mountains of Siberia has revealed the existence of a previously unknown hominin species around 30,000–50,000 YBP, genetically distinct from both Neandertals and *H. sapiens* (Krause et al. 2010). Studies of mitochondrial DNA from contemporary populations in sub-Saharan Africa strongly supported a model of human origins in Africa: contemporary sub-Saharan African populations were found to have approximately twice the amount of mitochondrial sequence diversity as non-African populations, as would be predicted for a region with the longest history of human occupation (Kivisild 2015).

Mitochondrial DNA studies, both ancient and modern, have been used in conjunction with archaeological evidence to track the migration history of *H. sapiens* out of Africa and across the world. By correlating estimates of sequence mutation rates to the number of mutations in different lineages since they diverged, the coalescence times of haplogroups to their most recent common ancestor (TMRCA) can be calculated, allowing migrations to be put into a temporal context. For example, the TMRCA for sub-Saharan African lineages (L0–L6) has been estimated to be 171,500 $\pm$ 50,000 years before present (YBP), which is roughly congruent with archaeological and fossil evidence for the emergence of anatomically modern *H. sapiens* (AMHS). All non-African haplogroups can be classified into just two macro-haplogroups, M and N, which last shared a common ancestor with African clades between 62–95,000 years before present. The Americas were the last continents to be peopled, via one or more movements out of Beringia, which was a continental connection between North America and Asia during the Last Glacial Maximum (~28,000 and 18,000 cal BP). The observation that pre-European contact indigenous American populations harbored the least mitochondrial genetic diversity compared

to other populations worldwide is consistent with the model that the Americas were the last continents to be peopled (approximately 15,000 years YBP). (Behar et al. 2008; Kivisild 2015)

Mitochondrial genetic diversity can be used to identify significant demographic events in past populations, including temporal changes in effective population size (N_e) (the number of individuals who contribute offspring to the next generation) and genetic bottlenecks, gene flow, or population expansions. For example, a recent study of Neandertal mitochondrial genomes supported a hypothesis that their Denisovan-like maternal lineages were largely replaced by gene flow from African hominins with mitochondrial lineages more closely related to AMHS, sometime prior to 270,000 years before present. (Posth et al. 2017)

SEE ALSO: DNA: Next Generation Sequencing; Genetics: Ancient; Genomics: Ancient; Sequencing DNA

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DNA: Next Generation Sequencing

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Since the discovery of the DNA double helix in 1953, a lot of progress has been made in order to read, or sequence, the DNA. The first method, now known as Sanger sequencing (Sanger, Nicklen, and Coulson 1977), utilized chain-termination. This process involves a single-stranded DNA molecule, a primer (a starting block, usually a 15–20 base pair synthetic DNA molecule) and deoxynucleotidetriphosphates (dNTPs), that is, the bases (A, C, T, and G) that will build a new string of DNA; when a modified dNTP is added, the chain breaks and a signal is sent off and that is when the sequence is read. This technique mirrors the polymerase chain reaction (PCR), where the same reagents are used (primer, dNTPs) plus a controlling/working enzyme (Taq polymerase), this time to copy the single DNA strands rather than sequencing them. By copying each molecule, within a few cycles millions of identical DNA molecules have been produced.

This platform has been updated and automated since the 1970s, and can now analyze 384 samples in a single batch with 24 runs per day. However, the newer, next generation sequencing (NGS, also called high throughput sequencing) has revolutionized DNA sequencing in general, and has caused explosive growth in the research field of ancient DNA (aDNA) (Krause and Pääbo 2016). There are two main reasons for this. First, only very short segments of DNA (35–150 base pairs, bp) can be obtained from archaeological samples. The aDNA has already been fragmented by chemistry and time; this fragmentation starts to happen directly upon an organism's death. Second, instead of relying on traditional Sanger sequencing to obtain one sequence per sample, by using NGS platforms one obtains many thousands of sequences per sample. A single run can now

produce up to a million reads (Linderholm 2016). So even though the aDNA is heavily degraded into short fragments (40–50 bp), with thousands of sequences obtained from a single sample, alignments can be made and longer stretches of DNA can be assembled and read, thus taking the aDNA field from genetics into genomics.

There are two technical concepts responsible for this huge achievement of obtaining millions of reads from one sample/run: sequencing by ligation (SBL) and sequencing by synthesis (SBS). Different commercial companies have used variations of these to release their own proprietary platforms (Goodwin, McPherson, and McCombie 2016).

Roche was the first company to develop and release a NGS platform, when they introduced the so-called 454 platform back in 2005. The platform utilizes pyrosequencing as the basic technology, rather than traditional Sanger sequencing. This new system was capable of sequencing roughly 400–600 megabases of DNA per 10-hour run. One year after the release of the 454 machine, a paper was published in *Nature* investigating Neanderthal remains using the 454 for the first time on archaeological material, launching the use of NGS in the field of aDNA (Green et al. 2006). The 454 platform used emulsion PCR as the template amplification strategy, and this technique paved the way for several other platforms/machines such as the Ion Torrent. The emulsion PCR is a system in which micelle droplets (similar to oil drops in water) are loaded with primer, DNA template, dNTPs and Taq polymerase, creating millions of independent PCR machines. The amplification itself happens when the template hybridizes to bead-bound primers; once the amplification has taken place the complement strand disassociates, leaving bead-bound single-stranded DNA (ssDNA) templates. These templates can then be sequenced, adding one base at a time, utilizing the light emitted as a signal of base incorporation (a form of SBS). The 454 was discontinued in 2013 and technical support of the platform will end in 2016. Although the 454 platform has been discontinued, some laboratories

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are still using the machine, and more papers will likely be published using results obtained from this platform.

Not long after the 454 platform was introduced, Solexa released a new form of NGS platform, the Genome Analyzer (GA). Illumina subsequently acquired Solexa, and rapidly released a string of commercially available NGS machines, MiSeq and HiSeq being the two most utilized machines in laboratories across the world. They have been the dominant platforms used in any genetic field, but are particularly preferred for aDNA research (Goodwin et al. 2016). The Illumina platform uses a solid glass surface (a flowcell with 1, 2, or 8 lanes) covered with a coating of surface-bound primers (p5 and p7) that are complementary to the library adaptors (a mirror piece of the primer DNA sequence). These will capture individual molecules and, via “bridge PCR” (an amplification step), create a cluster. The bridge PCR works as follows: the surface is washed with a mixture of dNTPs and polymerase. Priming occurs as the free end of the captured fragment bends or “bridges” to a complementary oligo on the surface. Repeated cycles of this step results in localized amplification of individual DNA fragments across the surface of the flowcell. On one flowcell there can be up to 200 million individual clusters, each with 1,000 copies of each original fragment. Once the clusters have been created, sequencing takes place, using the reversible terminator-based method. Here each single base (all terminator-bound dNTPs) is incorporated, the fluorescent dye (one for each base) is identified by laser excitation (using four different color emissions to determine the base that has been incorporated), and an image is created. The dye is then cleaved to allow the next round of nucleotide incorporation. Base calls are then made from these images (another example of SBS) (Mardis 2008).

ThermoFisher is the only company that has based the template amplification strategy on sequencing by ligation (SBL), with the NGS SOLiD wildfire; it uses a solid-phase template walking system. This sequence extension method uses DNA ligase rather than polymerase in conjunction with one- or two-base-encoded probes to read the DNA molecule.

One of the biggest developments for the NGS platforms has been paired-end (PE) sequencing.

This allows the DNA molecule to be read in both directions (forward and reverse), giving the investigator twice as much information from each extracted fragment for the same cost and time. Prior to this development, only one of the DNA strands was read.

The process of obtaining a sequence or whole genome (i.e., the entire genetic material from an organism) is as follows (i.e., from sample to sequence):

1. *Extraction:* The first step is to extract the DNA from the sample (bone, teeth, hair, tissue, soil, or water). There are several methods for this, depending on the platforms to be used or on the sample material (Rohland and Hofreiter 2007).
2. *Library build:* Regardless of platform, the next step after the DNA has been extracted is to build a “library” (Head et al. 2014). Since aDNA is already fragmented what is left to do is to index the samples. This is especially true if you plan to run multiple samples on one lane, that is, pooling samples. For double-stranded libraries, building is an easy three-step process (using a commercial kit). If the sample is less well preserved, older, or unique, a single-stranded library can be built following the same principles, but the lab procedure is slightly more complicated and more expensive.
3. *Quantification:* NGS is a technique that depends on adding a precise amount of fragmented DNA onto a solid surface. This means that it is imperative that the DNA is quantified as accurately as possible. Currently there is no gold standard for this. Once the library has been built it needs to be checked for quality and quantity. To check the quality, a Bioanalyser or a TapeStation (Agilent) can be used. To check the quantity, two routes are possible, fluorometry (Qubit, ThermoFisher Scientific) or real-time PCR (qPCR). Libraries can either be pooled, based upon the results from the previous step (to give equimolar amounts of each library to make the run unbiased), or put straight to be sequenced.

4. *Cluster generation and sequencing:* The samples are then run on one of the available platforms; the choice depends on the question, time and/or money.
5. *Data analysis:* Once the NGS data have been obtained, they undergo several steps before they can be used. Quality control is the most important one; initially the sequence processed is scored and the sequences are given as FastQ files. These files will include both the DNA sequence and the quality score for each base in the sequence. This score measures the confidence of it being called/read correctly by the sequencer.
6. *Pipelines:* To analyze the FastQ files, a whole range of bioinformatic software tools are available. Most aDNA laboratories have a proprietary pipeline. The pipelines include multiple steps: (a) removal of any residual adaptor sequences; (b) removal of poor-quality sequences; (c) checking for authentic DNA sequences; (d) removal of any tiling (i.e., a multitude of the same sequence); (e) assembly of the authenticated sequences; and (f) blasting (comparing) of the sequences against a known reference sequence or against the online database GenBank. Once these steps have taken place, the coverage (that is, the average number each base has been sequenced/covered) can be determined.
7. *Data presentation:* By using any number of programs such as TREEMIX, Plink, MEGAN, or GeneWiz, graphs and phylogenetic trees can be created to visualize the data obtained.

Because of the multitude of short reads generated from aDNA, the computational resources needed to analyze and store these datasets is considerable. One run can equal 1 Tb of data. The use of computational clusters has risen in the last five years as a consequence.

As each run produces more and more data, even outpacing Moore's law, the price per run has dropped significantly. Today it is possible to sequence a whole human genome for under \$1000; when the first human genome was sequenced it cost more than 3 billion dollars. This

price drop and increase in data has made this technology much more available.

SEE ALSO: Chromosomal DNA; DNA: Mitochondrial; Genetics: Ancient; Genomics: Ancient

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FURTHER READING

This technology is moving fast, so instead of recommending further readings, I suggest a search for the latest updates by typing in NGS on any search engine such as PubMed or Google Scholar.

Embodiment

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researchers have also evaluated the relationship between object/subject, boundaries between animate/inanimate, locus of personhood (e.g., the head in many societies), and additional cultural categories when reconstructing the past.

Embodiment in archaeological discourse

The term “embodiment” first appeared in the vast and multifaceted research regarding “the body” during the 1970s. Since this term is rather fluid, definitions and studies of it are rather extensive. However, Turner (2003, xvii) offers a useful explanation of the term that is applicable to archaeological studies that deal with the reconstruction of past societies through the study of material culture. For Turner, embodiment represents an attempt to understand human practices that are organized around the life course of an individual, including different life stages such as birth, maturation, reproduction, and death.

One of the best archaeological assessments of embodiment comes from Meskell and Joyce (2003) in their book *Embodied Lives: Figuring Ancient Maya and Egyptian Experience*. In their study, Meskell and Joyce (2003) examine the interrelatedness of representations (visual, written, and material) of bodily practices that include body modification, adornment, clothing, cosmetics, and human–animal relations. Their goal was to explore the essential notions of the body and reconstruct the living experiences of human beings and their underlying principles. In this respect, Meskell and Joyce (2003, 17) transcend the Cartesian dichotomy of mind and body interpretation, thus opening the possibility of framing embodiment as a concept distinct from notions of duality, hierarchy, and rational privilege. Other archaeologists have since questioned contemporary assumptions of binary sex structure systems (male/female), sex and gender dichotomies (when assigned biological sex and gender perceptions do not align), and locus of gender (features in the body that represent maleness, femaleness, or other gender(s)). Beyond these sex and gender reconsiderations,

Embodiment in bioarchaeological studies

While material culture has been extremely useful in examining certain aspects of embodiment in ancient societies, it is limited because it does not reflect all facets of an individual's lived experience. Viewed from a different perspective, Nancy Krieger (2001), a social epidemiologist, defines embodiment as a term that refers to how people literally incorporate, biologically, the material and social world in which they live, beginning in utero and continuing until death. In this context, the study of embodiment from the medical/social perspective is relevant today, as embodiment can be seen as a lens through which to study inequality or disparities such as (1) differences in living conditions that have a direct effect on the body, and (2) how the body can indicate social stress (suffering) or stigmatization that a group experiences.

From a bioarchaeological perspective, the body can be conceptualized as a malleable canvas that imprints both conscious and subconscious processes. Researchers have explored the biological imprints of lived experiences from human remains, such as embodiment in the past. In fact, the publication of *The Body as Material Culture: A Theoretical Osteoarchaeology* by Joanna R. Sofaer (2006) theoretically positions the physical body at the forefront of theories of embodiment by considering the body as a form of material culture inextricably linked to particular social and historical processes. While this book is one of the most cited works when discussing embodiment from the bioarchaeological perspective, other scholars such as Buikstra and Scott (2006) indicate that researchers need to be careful with such an approach. In their view, Sofaer (2006) does not consider all the factors

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that may impact the body, including cultural and historical dimensions, genetics, and other biological processes. Buikstra and Scott (2006) suggest that both the biological and social body must be interpreted together through a highly contextualized study of mortuary contexts.

Although the term “embodiment” permeates the recent bioarchaeological literature, some studies have been more successful at linking theoretical models and empirical data. A few examples of this work offer an integrated approach to specific questions regarding embodiment in the past.

Sex and gender

In a short yet relevant report, Walker and Cook (1998) alerted readers of the *American Journal of Physical Anthropology* to the distinctions between the terms sex and gender, as quite often both terms have been used as synonyms. In brief, according to these authors, sex refers to the biological differences between male and female, while gender refers to the socially constructed roles that individuals may have in society. Bioarchaeologists typically assess sex based on a series of morphological traits, while gender is interpreted through an archaeological lens that includes clothing, hairstyles, grave goods, imagery, and historical descriptions. However, some researchers have raised concerns, stating that sex cannot be based solely on bone morphology, and furthermore the interpretation of the gendered body and gender roles through the study of mortuary contexts may be limited as the funerary ritual is most likely created by mourners.

These researchers argue that a better understanding of gender in the past can be seen through the study of human remains, as socially constructed gender categories through performative actions and/or habitual activities are embodied in the biological body. For example, the study of auditory exostosis has been used for this purpose. An auditory exostosis is an abnormal bone growth within the external auditory meatus of the temporal bone that develops as the result of sustained and frequent participation in aquatic activities. Based on this theory of causation, researchers have been able to identify gender roles in the past. Standen, Arriaza, and Santoro (1997) detected a relatively high prevalence of

auditory exostoses among adult males in past Chilean populations that lived along the Pacific Coast. Males were more likely to be engaged in sustained aquatic activities (e.g., fishing) based on gender roles, and this social practice became embodied in their bones through formation of auditory exostoses.

Other researchers have used a similar approach to challenge binary concepts of gender roles in the past, as many societies recognize more than two genders. Osteological markers such as musculoskeletal stress markers (MSM) of female-associated daily activities in male skeletons and vice versa have been interpreted as evidence of a third gender (Hollimon 2017). Other activity-associated markers that have been used to infer gender roles from human remains include degenerative joint disease (DJD), squatting facets, and dental wear patterning.

Cranial modification

Cranial modification represents the intentional reshaping of the head of an individual, beginning shortly after birth, which requires significant time and societal investment to be successful (see CRANIAL SHAPING). This practice was common in the past in the Andes and, in conjunction with ethnographic and archaeological data, researchers have used this permanent body alteration as an example of embodiment in the past. For instance, in the highlands, cranial modification embodied geographical borders among the Tiwanaku, as there were clear regional patterns of cranial types. On the other hand, head shapes embodied the lived experiences and worldview of different occupational subgroups or ethnicities, such as with the coastal Chiribaya, including those who were dependent upon a marine-based subsistence versus farmers who depended on agriculture. Both groups had their own distinctive head shape.

In Mesoamerica, head modification in past societies such as the Maya was a common practice, although researchers have outlined a different scenario. The process of molding the head prevents the wandering of the soul of infants, while also crafting them into adults. These and other topics regarding embodiment and cranial modification are addressed in the edited volume

by Tiesler and Lozada (2018) who suggest that head shape embodies deeper understandings of ontological notions of the being and of the native cosmos in ancient Mesoamerica and the Andes.

Other forms of body modification

While cranial modification was initiated when an infant was born, dental decoration among the Maya embodied life stages such as the transition from childhood to adulthood. Central incisors were shaped similar to the Mayan sign for *ik*, a term that alludes to wind or breath, and interpreted as a source of vitality during this rite of passage (Scherer 2018).

Bioarchaeologists may not have the opportunity to fully study the impact of other permanent forms of body modification from skeletal remains. However, from anthropological and historical accounts there is ample evidence for the permanent manipulation of the body that includes foot binding and neck rings, and many others. Foot binding in ancient China during the initial years of its practice embodied the lifestyle of certain upper-class women who did not need to move. Historical records suggest that they spent most of their lives in a sitting position as their bound feet hindered their ability to walk. Similar to cranial modification, and unlike other forms of body modification, foot binding was a social imposition, and once the natural anatomy of the feet was reshaped, this process could not be reversed.

The use of neck rings has been documented among the Paduang women living in Burma, and, unlike cranial modification and foot binding, this practice still exists. Legend says that the rings around the neck protected women from tiger attacks; however, researchers seem to agree that a long neck coiled with brass rings represented an elite symbol. Today, it is mostly used to attract tourists. While the meaning of these body alterations transformed over time, researchers such as Stone (2012) propose that these practices embody indirect modes of structural violence toward women in these societies.

Diseases

As certain chronic and endemic diseases leave indelible marks in the body, numerous case

studies document how people embodied their biological and social living conditions in the past. These conditions were shaped by genetic and biological factors as well as the social and physical environment. For instance, urbanization resulted in changes in living conditions (environmental and social), such as increased population density. This change in living conditions allowed for the transmission of tuberculosis in the past, to the extent that the detection of tuberculosis in human skeletal remains can be seen as one sign of increasing urbanization. Another example of disease-associated embodiment can be seen in chronic illnesses such as juvenile idiopathic arthritis (JIA), a type of arthritis that affects children and young adults. Skeletal evidence of this condition was reported by Buikstra et al. (1990) who describe a juvenile skeleton dated to 900–1050 CE in southern Peru. The extensive osseous lesions of this individual suggest that bipedal locomotion, functional use of the upper extremities, and mastication would have been difficult if not impossible, and that the onset of the disease was probably very early in life. This condition also left important clues regarding the individual's social conditions through embodiment, revealing how the community cared for and culturally viewed individuals with chronic, debilitating conditions such as JIA.

SEE ALSO: Bioarchaeology; Bodies and Embodiment; Degenerative Joint Disease; Dental Decoration; Gender and Sexuality; Osteology; Paleopathology

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Estimating Adult Age at Death: Cranial Suture Closure

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The estimation of age at death, along with sex, is one of the primary objectives of skeletal analysis conducted by both bioarchaeologists (see BIOARCHAEOLOGY) and forensic anthropologists. Because of the importance of estimating age at death as precisely and accurately as possible, a large number of techniques and methods have been developed using various skeletal elements and features, including the skull. These methods are generally divided into those appropriate for estimating age for immature versus adult remains, with methods for immature remains tracking the growth of the individual (see ESTIMATING SUBADULT AGE: DENTAL DEVELOPMENT AND ERUPTION; ESTIMATING SUBADULT AGE: DIAPHYSEAL LENGTH; and ESTIMATING SUBADULT AGE: EPIPHYSEAL UNION) and methods for adult remains tracking their progressive breakdown (see ESTIMATING ADULT AGE: AURICULAR SURFACE MORPHOLOGY; ESTIMATING ADULT AGE: PUBIC MORPHOLOGY; and ESTIMATING ADULT AGE: TRANSITION ANALYSIS). One technique to estimate the age at death of adult remains is by observation of closure of the cranial sutures—the lines of contact between individual bones of the skull.

Cranial suture closure techniques are based on assessment of an individual's degree of cranial synostosis—the fusion of adjacent bones of the skull at the sutures. Because cranial bone growth occurs at the sutures, they tend to remain open (barring precocious closure in the case of craniosynostosis) during childhood and adolescence. Following cessation of growth—generally between 18 and 25 years of age—these sutures begin to progressively fuse in a predictable pattern. With advanced age, this

process can eventually result in no, or very little, visible division between individual bones. When presented with cranial remains, skeletal biologists can assess both the degree and pattern of cranial suture closure (i.e., which sutures have fused and which remain open) to estimate age at death.

Cranial suture closure is unusual among analytical techniques frequently employed by skeletal biologists in that it has a remarkably long history of academic investigation. The fusion of cranial sutures with age was first described by the father of comparative anatomy, Andreas Vesalius, in the mid-sixteenth century and has remained a topic of inquiry and debate until the present day (see Masset 1989 for a comprehensive review). While numerous specific techniques for estimating age at death from suture closure have been proposed, most modern applications largely derive from the methods developed by Meindl and Lovejoy (1985). One-centimeter sections at 11 points on the skull are scored according to degree of closure. The sum of these scores corresponds to a mean age at death and an estimated age range for the given degree of fusion. These age ranges were derived from observation of cranial suture closure among a reference population, or a comparative sample for which age at death is known.

While scoring degree of fusion at established points on the cranium remains fairly standard, there continues to be considerable disagreement on which sutures or series of sutures provide the most accurate estimations of age at death. For example, earlier scholars argued that sutures occurring on the external surface of the cranium (ectocranial sutures) are more reliable for estimating age at death than those visible on the internal surface of the cranium (endocranial sutures), while more recently the opposite has been suggested (Meindl and Lovejoy 1985). Separate techniques based on other suites of sutures, most notably those of the palate, have also been proposed (Beauthier et al. 2010; Mann et al. 1991). Furthermore, there is considerable debate as to how demographic factors, such as ancestry and sex, can influence the rate of suture closure.

For example, Nawrocki (1998) found that the rate and pattern of suture closure differed between individuals of African versus European descent, as well as between males and females. Findings such as these have led some to argue for the development of population-specific reference samples, so that the age distribution of the reference sample approximates the age distribution of the studied population as closely as possible (Masset 1989). Other researchers argue that ancestry and sex have zero or negligible effect on cranial suture closure, and are therefore irrelevant when estimating age at death from sutures (Meindl and Lovejoy 1985).

Even when cranial suture closure aging can be performed, there remain pitfalls. All techniques for estimating age at death for adult remains result in age ranges that are incredibly wide, particularly among older individuals, a result of the extreme level of individual variation in suture closure. Also, because most cranial suture closure techniques rely on composite scoring of multiple sites on the cranium, by definition all must be preserved for age estimation to be conducted. If even one requisite location for a given technique is unobservable, then aging based on suture closure is impossible. This can be especially problematic in archaeological contexts in which skeletal remains, and particularly delicate cranial bones, tend to be highly fragmentary. However, a more recently developed aging technique, transition analysis, utilizes cranial suture closure along with other age estimators (including pubic symphysis and auricular surface) but does not require a completely preserved suite of sutures. Instead, an individual maximum likelihood age estimate is obtained for each individual and incorporates uncertainty introduced by missing data. Sutures are the least useful indicators incorporated into this method; however, partial suture data can be incorporated into age estimates based largely on other diagnostic skeletal features (Boldsen et al. 2002).

Given these considerations, it is perhaps not surprising that, from a survey of skeletal biologists, Garvin and Passalacqua (2012) found that cranial suture closure ranks among the least desirable techniques for estimating adult age at death. In fact, cranial suture closure methods are typically used only when preferable techniques, such as pubic symphysis and auricular

surface morphology, are impossible. When cranial suture techniques are utilized, it is generally only to broadly establish the individual's stage of adulthood and preferably only in conjunction with other, more reliable aging techniques. For example, Buikstra and Ubelaker (1994) recommend a hybrid approach, utilizing ectocranial, endocranial, and palatal sutures to broadly sort an individual into young (20–34 years), middle (35–49 years), or old (50+ years) adulthood.

Despite these concerns and issues, cranial suture closure remains a frequently used tool for estimating age at death for adults for the simple fact that cranial remains are among the most commonly preserved skeletal elements in both archaeological and forensic contexts that can provide information about adult age at death. This is particularly true compared to fragile features like the pubic symphysis, which are more robust for estimating age at death, but are also relatively fragile, and, therefore, frequently suffer from poor preservation. Furthermore, cranial suture closure remains one of the few methodologies available to estimate age in older adults, particularly in cases where dentition is not preserved (Meindl and Lovejoy 1985). As a result, researchers continue to devote efforts to refining techniques and expanding reference populations to continually improve the usefulness and precision of cranial suture closure techniques, particularly through the use of virtual imaging technologies such as computed tomography (CT) (see COMPUTED TOMOGRAPHY) (Chiba et al. 2013). While unfortunately little concrete progress has yet been made on these fronts, these recent developments indicate that the long history of estimating adult age from cranial suture closure is unlikely to end anytime soon.

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Estimating Adult Age: Auricular Surface Morphology

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The auricular surface is located on the posterior portion of the ilium and has been used to estimate adult age at death since 1985 and is typically used in combination with other skeletal age estimators (see ESTIMATING ADULT AGE: PUBIC MORPHOLOGY and ESTIMATING ADULT AGE: TRANSITION ANALYSIS). The auricular surface is often utilized because it is robust, surviving the burial environment much more often than the fragile pubic symphysis (see ESTIMATING ADULT AGE: PUBIC MORPHOLOGY), and because age-related changes continue into the later decades of life. It is likely that the anatomy of the sacro-iliac joint influences age-related changes.

The auricular surfaces of the ilium are part of the sacroiliac joints (SIJ) between the sacrum and the left and right ossa coxae (pelvic bones). The size and shape of the auricular joint surfaces are variable between individuals and between the left and right sides of an individual. The SIJ is a complex joint which allows a small amount of movement (although the degree of movement is debated) and is stabilized by ligaments. In the final stages of pregnancy, hormones allow the ligaments to relax, allowing for greater movement of the SIJ during childbirth (Vleeming et al. 2012). Despite this, few sex-related differences in the rate of aging have been reported. The inferior portion of the joint is synovial, whereas the superior portion of the joint is more fibrous. On the sacral side, the joint surface is covered with a thick layer of hyaline cartilage, whereas on the iliac side it is covered with a thin layer of fibrocartilage in childhood which progressively changes to hyaline cartilage with maturation (Vleeming et al. 2012). Similar age-related changes are not observed on the sacral side of the joint; this is probably due

to the differences in anatomy. Fusion of the SIJ is seen in a small percentage of older individuals (usually over 50 years of age and more commonly in males) and is associated with some pathological conditions, such as ankylosing spondylitis and diffuse idiopathic skeletal hyperostosis (DISH).

The first formal method developed to estimate age from the auricular surface was by Lovejoy and colleagues (1985) based on observations of the Libben population (archaeological) and the Todd Collection (known-age). They described typical features of auricular surfaces which were grouped into six five-year, one ten-year, and a final, open-ended age groups. These narrow age ranges do not appear to reflect the range in age variation seen for each of the auricular surface stages (Osborne, Simmons, and Nawrocki 2004) and have low levels of accuracy. Indeed, Lovejoy et al. (1985, 21, 23) originally noted that they selected some individuals for photography that fell outside their modal age group. Key features associated with the aging process of the surface itself were billows (which are transversely organized and reduce in depth to striae), microporosity and macroporosity (which appear with increasing age), grain (the joint surface becomes more coarsely granular with increasing age), and density (which refers to the increasingly solid surface appearance of the bone and which replaces coarsely granular bone). These are associated with changes to the apex (the edge of the joint adjacent to the end of the arcuate line) and the retroauricular area (located posterior to the joint surface). Changes in the latter two areas were referred to as increasing “activity” by Lovejoy and colleagues.

In 2002, Buckberry and Chamberlain (2002) published the “revised auricular surface” method, which recorded five features of the surface (transverse organization, surface texture, microporosity, macroporosity, and apical changes) independently, before combining them as a composite score to estimate age. The features utilized were based on those of Lovejoy and colleagues and were quantified by assessing either the percentage of the surface or which of the two demifaces were affected. Age was presented as 100 percent ranges

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and mean ages for seven auricular surface stages. The age ranges reflect variation in auricular surface appearance and as a result are very wide. While this increases accuracy compared to the Lovejoy method, these ranges are imprecise. The revised method included a Bayesian analysis of the data, assuming a uniform prior probability of age, thus removing the biases introduced by the reference sample (Christ Church, Spitalfields), which is skewed towards older ages.

Tests of the methods have shown that the auricular surface seems to vary little between the two sexes and different ancestry groups. Population-level differences are observed, but this is probably partially a result of the comparison of known age against reported mean age estimates (which reflect the age structure of the reference sample); unless the reference sample and the target population have a similar age-at-death structure, high levels of bias and inaccuracy will be evident. Bayesian statistics have been used to develop paleodemographic profiles (see PALEODEMOGRAPHY AND HAZARDS ANALYSIS) that are not influenced by the age structure of the reference sample and have been used successfully to investigate catastrophic mortality during the Black Death and to compare archaeological populations in Japan (for example).

The auricular surface was included in transition analysis (see ESTIMATING ADULT AGE: TRANSITION ANALYSIS). In this method, auricular surface traits are particularly useful for estimating the age of older individuals, and the trait “posterior iliac exostoses” specifically has been noted as a trait of old age. Attempts to apply auricular surface age estimation to 3D images have had limited success and it is likely that new methods would need to be developed to apply to 3D models of auricular surfaces, as many features (grain, striae, microporosity) are hard to capture using laser scans or computed tomography (CT) scans. Future research should address more robust statistical methodologies for

combining age-related data, estimating individual age, and presenting the probability of age of an individual.

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Estimating Adult Age: Pubic Morphology

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A number of techniques are commonly employed for estimating age at death such as epiphyseal fusion, cranial suture closure, dentition (formation, eruption, and attrition), and age-related changes to the pubic symphysis, auricular surface, and sternal rib ends (Garvin et al. 2012). The pubic symphysis is the cartilaginous joint found in the midline on the anterior plane connecting the right and left halves of the pelvis. It is considered the most reliable skeletal age indicator and is therefore the most frequently applied technique (Garvin et al. 2012). Morphological changes that occur on the pubic symphysis appear to travel along a distinct seriation that is irreversible. Moreover, these changes occur throughout one's lifetime, well into old age, whereas many skeletal age-estimation techniques such as epiphyseal fusion and dental formation are only used to estimate the age of subadults.

Age-related changes of the pubic symphysis were first documented in 1920 by Todd. Todd (1920) generated a ten-phase system, with each phase defined by a morphological description paired with an age range. The early phases describe post-adolescence when the pubic symphysis expresses billowing, followed by the changes that occur throughout middle-aged adults such as definition of the upper and lower limits of the face, filling in of the ridges and furrows, and the formation of a symphyseal rim. The final phase encompasses all individuals 50 years and older, when features are no longer developing but rather degenerating. This final phase is defined by the breakdown of the symphyseal rim, erosion of the symphyseal face, and lipping along the margins. Todd (1920) concluded that the rate of degeneration was not associated with

differences between ancestries or sexes, and the variation observed on female pubic symphyses was not due to the effects of parturition, or childbirth.

McKern and Stewart (1957) argued that the phases put forth by Todd (1920) were too specific and the age ranges too narrow to accurately capture the variation observed at each age. They proposed a component system based on the dorsal plateau, ventral rampart, and symphyseal rim that generates a composite score, which is connected to age ranges. This three-component system was later concluded to be applicable to a female sample; however, this method seriously underestimates the age of older skeletons of both sexes, and is therefore no longer widely used (Garvin et al. 2012).

Katz and Suchey (1986) believed the McKern and Stewart method proved too difficult to utilize for an inexperienced analyst and decided that a six-phase system derived from the original ten phases from Todd performed most accurately. Then, Brooks and Suchey (1990) acknowledged the need for a female standard because of the morphological differences due to parturition. The individuals in their sample consisted of males and females derived from four different continents and various socioeconomic backgrounds. Thus, the Suchey–Brooks method is a six-phase, sex-specific method for age estimation using the pubic symphysis, and is the most commonly used today. Accuracy of this method is dependent on an observer's ability to accurately assign a numerical phase to various morphological changes observed on the pubic symphysis (Garvin et al. 2012).

In order to combat issues with age-mimicry and small sample sizes, the field of age estimation is moving from description of phases to transition analysis (see ESTIMATING ADULT AGE: TRANSITION ANALYSIS). Transition analysis utilizes a Bayesian approach (see BAYESIAN STATISTICS) for skeletal age estimation by using uniform priors and likelihood functions to make inferences on the timing of the transition from one phase to the next. This method helps better identify older age

cohorts, which historically has been a limitation of earlier methods because the last phase is the largest, most encompassing phase. Transition analysis returns to using a component-based system, but attaches a statistical probability of that individual being in each of the expressed phases for each component, given that population (Boldsen et al. 2002). Transition analysis is ideal for single skeletal age indicators such as the pubic symphysis because the currently employed techniques are defined by discrete stages where no specific set of features are repeated (Boldsen et al. 2002; Garvin et al. 2012).

Accurate estimation of age relies on the assumption that the individual being analyzed is biologically similar enough to the reference population to follow the same rate of degenerative change. As a result, recent studies promote the need for population-specific standards that focus on specific combinations of age, sex, and ancestry (Garvin et al. 2012). Additionally, the application of statistical methods such as transition analysis to age-estimation techniques continues to progress the field. With a focus on improving and increasing accuracy, research on pubic age estimation continues to expand worldwide.

SEE ALSO: Bioarchaeology; Osteology; Paleodemography

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Estimating Adult Age: Transition Analysis

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Transition analysis is a statistical procedure designed to estimate the age of human skeletons. At present, this approach has been applied to adult skeletons, although nothing prevents its extension to juveniles. Introduced by Boldsen and colleagues (2002), transition analysis addresses difficulties with standard procedures first identified by Bocquet-Appel and Masset (1982) that result in biased age estimates. Problems with commonly used adult age-estimation procedures are so pervasive that no confidence can be placed on age-specific mortality patterns, life expectancy, or longevity generated from them.

There are two ways to collect age-related skeletal information. Entire anatomical structures, such as the pubic symphysis, can be arranged in a sequence of stages from young to old. The observer essentially integrates various age-informative features when deciding which stage most closely matches the specimen of interest. Alternatively, different aspects of an anatomical structure are scored as separate components, and the resulting information is combined through a formal analytical process. Transition analysis is an analytical, component-based approach to age estimation based on the pubic symphysis, sacroiliac joint, and cranial sutures.

In standard procedures, a skeleton's age is estimated directly from the age distribution of individuals assigned to a given stage in the reference sample. The resulting age-mimicry seriously biases estimates of age for individual skeletons and undermines paleodemographic findings (Bocquet-Appel and Masset 1982). That problem is avoided in transition analysis by estimating the

probability of being in a given stage conditional on being each age (e.g., each year) throughout the human lifespan ($P(stage|age)$). First, the age-at-transition from one stage to the next is estimated through sigmoid curves (Boldsen et al. 2002). Sigmoid curves permit the identification of the mean age of transition and confidence intervals, assuming a symmetrical distribution around the mean. A stage-specific likelihood function is estimated by subtracting the probability of having entered the next higher stage at any age from the probability of having entered the stage in question. These likelihood functions, one for each stage, are not affected by the reference sample's age distribution. However, a sufficient number of skeletons spread throughout adulthood is needed to generate curves with sufficient confidence for age estimation.

The likelihood functions for different components are then combined to estimate the age of a skeleton given that it was assigned to a particular multivariate stage ($P(stage|age)$). That is, the age of a skeleton from an archaeological or medicolegal context is estimated by combining the probability distributions for each observed trait. This procedure yields the probability that an individual was a particular age, the following year, the next one, and so on.

For each skeleton, a point estimate (maximum likelihood) is produced and, of more interest, an age range. Estimates are only valid if conditional independence can be assumed. Boldsen et al. (2002) provided an ad hoc solution, but a mathematically satisfactory solution awaits further research. Furthermore, the estimates described above are generated assuming there was an uninformative, or uniform, prior distribution. The estimates can be modified for forensic and archaeological purposes by applying different prior distributions corresponding to mortality regimes characteristic of appropriate populations (e.g., United States homicides for forensic cases).

The use of sigmoid curves for each trait will work well for juvenile and young adult skeletal features that are strongly influenced by developmental processes, such as tooth

formation. Ongoing work with skeletal features related to senescent changes in adults, however, indicate that smoothed empirical transition curves might better characterize what has been observed in large and diverse skeletal samples.

In its current form, transition analysis works better than any other age-estimation procedure for adult skeletons. That still leaves much to be desired because individual estimates are often wide of the mark, and specific ages for the elderly are largely unsupported because there are few old-age indicators (Milner and Boldsen 2012). Together, however, the estimates approximate the true age-at-death distribution through middle age, although the upper end of the lifespan tends to be underestimated.

Those two challenges—poor individual estimates and an underestimation of old people—are currently being addressed, starting with systematic examinations of several tens of potentially informative age indicators distributed throughout the skeleton. Individually, these skeletal features provide little information about age because they are often classified simply as absent or present (i.e., young or old). Collectively, however, they hold much promise to judge from experience-based appraisals of age based on a large array of such features (Milner and Boldsen 2012). Incorporating these features in a transition analysis framework should yield more accurate estimates and provide a means to narrow age ranges, especially in middle to old age, that are often too long to be of much practical use.

SEE ALSO: Bayesian Statistics; Life Table Analysis; Paleodemography; Radiocarbon Calibration and Age Estimation

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Estimating Skeletal Sex: Cranial and Pelvic Morphology

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Anthropologists assess and quantify sexually dimorphic features, or features that exhibit differences in size and shape between the sexes, to estimate the biological sex of a skeleton. Even though sexual dimorphism is quantifiable in the subadult skeleton, sexually dimorphic differences are greatest following the pubertal growth spurt. Both the pelvis and cranium exhibit sexually dimorphic morphological features that are used to estimate the sex of unidentified skeletal remains. While metric and nonmetric methods exist, the methodological approach is largely dependent on the element(s) available and their condition. Generally, metric analysis reduces intra- and interobserver error and is more objective, while morphological analysis is more subjective and efficient. Because each case is unique, there is not an exact process to follow. However, one should always use a method that is reliable and valid.

The pelvis is widely recognized as the most accurate element for sex estimation because of the inherent differences due to reproductive requirements. Morphological methods are more common than metric methods for the pelvis, partly because of the problems associated with pinpointing well-defined, reliable landmarks on the pelvis. There are several morphological skeletal features on the pelvis to estimate sex (e.g., greater sciatic notch, obturator foramen, breadth of the pubic bone). A popular feature on the pelvis that contributes to sex estimation, but has received less research focus than other skeletal features, is the greater sciatic notch. The

greater sciatic notch can adequately (80%) separate males and females using an ordinal scoring system ranging from hyperfeminine (score of 1) to hypermasculine (score of 5).

Phenice defined the most frequently analyzed nonmetric traits, which are located on the pubic bone. Phenice traits include the ventral arc, subpubic concavity, and medial aspect of the ischio-pubic ramus. The three traits were assessed for simple presence or absence and yielded overall classifications of 96 percent. While the Phenice method was employed for several decades without modification, the methodology ignored the range of variation associated with the expression of each trait and how to assess the traits if they were ambiguous or inconsistent. Klales, Ousley, and Vollner (2012) revised the Phenice method by including a standardized ordinal recording system and incorporating a logistic regression model to predict the probability of sex membership based on the pelvic trait scores. The cross-validated mean classification rate was 94.5 percent, with low intra- and interobserver error (Klales et al. 2012). Recently, efforts have been made to incorporate contemporary skeletal samples from numerous countries in an attempt to develop a global model. In the event of unknown ancestry, a global recalibration equation increases applicability and the overall probability of a correct classification.

The cranium has historically been considered the second-best indicator and is commonly used in sex estimation by forensic anthropologists and bioarchaeologists. Both metric and nonmetric methods are regularly employed. The most popular statistically substantiated, nonmetric approach combines a five-stage scoring system for five cranial morphological traits (glabella, nuchal crest, mental eminence, mastoid process, and supraorbital margin) and employs discriminant function analysis to obtain correct classifications. Modern populations had classification rates up to 88 percent, while ancient Native American groups had classification rates up to 83 percent (Walker 2008). Recent studies have tested the accuracy of Walker (2008) on numerous contemporary

and historical populations and have proven that the given population on which the method was developed was extremely influential in classification rates. While the Walker (2008) method is effective, it has lower correct classification rates than methods using the pelvis, particularly when applied to other populations. While Walker's method remains frequently employed for its ease of use, further studies are being conducted to increase correct classification rates and better understand the underlying processes and covariation of traits. Such new methods are attempting to quantify shape differences in the previously defined cranial morphological traits. For example, Garvin and Ruff (2012) created a new quantitative methodology to test sexually dimorphic brow and chin morphology utilizing 3D surface scans. Browridge analysis returned a classification rate between 74 and 91 percent, while the chin returned a classification rate of 62–74 percent (Garvin and Ruff 2012).

As with most methods, population specificity is important to recognize prior to employing a method. Even though the effects of population specificity are historically recognized to be more substantial with metric methods, classification accuracies associated with morphological methods decline dramatically when they are applied to populations excluded from the reference sample. This holds especially true with cranial traits. The degree of sexual dimorphism varies around the world and is population dependent. Bioarchaeologists and forensic anthropologists should always

be aware of the population that the method was derived on prior to application.

While there are numerous methods to be aware of, as well as case-specific factors, it is strongly recommended that when estimating sex, emphasis first be placed on morphological analysis of the pelvis and then on metric analysis of the long bones and cranium. As with most aspects of the biological profile, the more elements evaluated and the more methods employed, the more likely a correct classification.

SEE ALSO: Craniometry; Estimating Skeletal Sex; Metrics; Geometric Morphometrics; Osteology

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Estimating Skeletal Sex: Metrics

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Sex estimation using metrics involves the analysis of single or multiple measurements based on osteological landmarks or on the maximum or minimum dimensions of cranial or postcranial bones that are sexually dimorphic. Analyses using single measurements are known as univariate analyses, and those using multiple measurements are known as multivariate analyses. A simple index may also be used, which is created using two single measurements. For both univariate and multivariate analyses, observed measurements are compared to a distribution of measurements from individuals of known sex and defined population, which results in sex estimations that are highly population-specific.

Both univariate and multivariate metric analyses usually involve the application of discriminant function analysis (DFA). This is a statistical method used to determine which variables discriminate between two or more naturally occurring groups, in this case males and females, and assumes a normal distribution of the sample for each measured trait. Univariate metric analyses and indices rely on a sectioning point calculated using DFA that is then used to reliably categorize males and females into separate groups for a given population. When used to estimate skeletal sex, DFA can utilize several different approaches including canonical discriminant functions and Mahalanobis distances (see STATISTICS IN ARCHAEOLOGY).

The first successful application of discriminant function analysis in sex estimation was a method developed by Giles and Elliot (1963) utilizing multiple cranial measurements, which was found to correctly estimate sex at a rate of 85%. Rates for correct classifications of African Americans and European Americans from the Forensic Data Bank (FDB) at the University of Tennessee range

between 83–93% and give a general indication as to the overall accuracy that can be expected of metric sex estimation using discriminant function analysis (France 1998). While craniometrics are useful, methods that are based on postcranial metrics have been found to show much greater accuracy, according to a comprehensive study of sectioning points based on postcranial measurements from the Forensic Data Bank (FDB) at the University of Tennessee (Spradley and Jantz 2011). Traditionally, methods based on multivariate measurements of the humerus, scapula, femur, and tibia are more accurate, more commonly used, and are supported by more extensive research than methods using other postcranial bones. One important conclusion by Spradley and Jantz (2011) was that the metric analysis of the pelvis, whether univariate or multivariate, was shown to rank lower in accuracy than expected relative to other postcranial bones, in spite of the standard assumption of the pelvis as a reliable indicator of skeletal sex by many anthropologists. One major drawback of using craniometrics and postcranial metrics to estimate sex is the fact that the majority of standards are highly population-specific. Thus, care must be taken in application to skeletal samples that are far removed in ancestry.

Fordisc, a computer program that uses discriminant function analysis, is based on a reference population comprising nearly 3,400 forensic cases from the University of Tennessee's Forensic Data Bank (Ousley and Jantz 2005). Fordisc uses both cranial and postcranial measurements to estimate sex and should only reasonably be applied to samples where the reference population is known to be included in the Forensic Data Bank for the version of Fordisc being used. The program also includes Howells' worldwide cranial data, which allows for greater accuracy in estimation sex, stature, and ancestry of archaeological samples.

Future work in estimation of sex using skeletal metrics involves the refinement of methods using bones that have not traditionally been used for sex estimation or for which few studies have been

attempted at a high level of statistical rigor, such as the patellae, ribs, and vertebrae. More research is also needed in testing relatively new methods that claim to be universal, or independent of specific populations. For example, a recent multivariate method using measurements of the pelvis and femur and logistic regression was able to correctly classify 95–97% of the sample of the population under study. According to the authors, the method is universally applicable as it is based on biomechanical differences between males and females; however, the method has not yet been widely tested (Albanese, Eklics, and Tuck 2008).

Another expanding field of study within metric sex estimation is the application of geometric morphometrics (see GEOMETRIC MORPHOMETRICS) to allow for comparison of measurements based on differences in shape while at the same time accounting for size differences. Geometric morphometrics allows researchers to analyze variability in shape in a more complex way than is possible with linear measurements alone. Geometric morphometric methods utilize 3D scanning, CT scanning, and specialized computer software that allows measurements to be captured across the whole surface, whereas standard metric analysis is dependent on discrete measurable landmarks. In addition, the use of geometric morphometrics may also help reduce the issues with intra-observer and inter-observer error that sometimes accompany metric analysis.

SEE ALSO: Geometric Morphometrics;
Statistics in Archaeology

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Estimating Subadult Age: Dental Development and Eruption

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The successive formation and emergence of the deciduous and permanent teeth in the mouth have been used to estimate the age at death of skeletal remains since the earliest forays into mammalian osteology by naturalists. For humans, dental development is traditionally considered to be the gold standard for age estimation of children's remains, and is often used to calibrate other aging methods, such as the comparative study of developing long bone lengths (see ESTIMATING SUBADULT AGE: DIAPHYSEAL LENGTH) that may be more directly affected by growth arrest or population variation. However, the most widely used standards (Schour and Massler 1940) suffer from significant sampling biases that undermine confidence in the precision of these methods. New standards (Al Qahtani, Hector, and Liversidge 2014), derived from better documented reference collections, show some improvement, as do histological methods that permit individual age estimates from the observation of microscopic internal features of tooth enamel.

Anatomists and anthropologists have long used the progressive emergence of the deciduous or primary teeth into the mouth and their replacement by the larger permanent teeth as a means to estimate age at death or the age of living children. Following the eruption of the permanent third molars at the end of the second decade of life, teeth provide a much less reliable means to estimate age; the wear of the occlusal surfaces of teeth can provide a population-specific broad estimate of relative age among adults, but it is much less accurate than other methods of estimating the age at death of adults.

The Schour and Massler standards

Pictorial representations of dental formation and eruption were first developed in the nineteenth century. These early chronologies were based on observations of developmental defects known as enamel hypoplasias. In the early twentieth century, Logan and Kronfeld dissected the teeth of deceased infants and fetuses to document dental development. Many of their subjects had died from infectious conditions or experienced developmental anomalies, so it is possible that their growth may have differed from that of healthy peers who survived childhood. However, dental development does appear to be under strong genetic control, and short-term developmental arrest causes little disruption to the chronology of tooth development overall. Schour and Massler (1940) modified this work by incorporating further evidence from the patterning of hypoplasias on tooth enamel. Schour and Massler's pictographic atlas of dental development continues to be used by many researchers for estimating the age at death of subadult remains and is pervasive in dental textbooks. This atlas shows the chronology and sequence of dental development and eruption in stages that are associated with chronological age ranges. The 21 stages of development in this chart depict the changes in dental development and eruption from five months in utero to 35 years of age. While the Schour and Massler (1940) standards are widely used, these early works were based on very small samples of children of European ancestry alone. In addition, later radiographic studies carried out on diverse populations show some population variability in eruption timing and sequence. Subsequently, Ubelaker published a minor modification of the Schour and Massler chart that he adjusted to better conform with eruption patterns described by radiological studies of Native American children. Ubelaker's chart is most commonly used in bioarchaeological studies in the Americas. Many bioarchaeologists also score the state of dentine, enamel, and root development on incompletely

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formed teeth as a more precise record of dental formation in subadult dentitions.

The London Atlas

More recently, Al Qahtani et al. (2014) have developed a dental development and eruption atlas that can be used to estimate the age at death for individuals between 30 weeks in utero and 23.5 years of age. This “London Atlas” is an improvement over earlier standards because the reference populations and methods are well documented; the atlas was based on a large series of radiographs, as well as prenatal and postnatal known age historical skeletal remains from London. The London Atlas is comprised of 31 stages of dental development that include more detailed depictions of tooth development, including the progression of enamel, dentine, and pulp. It appears to be more accurate than the Schour and Massler chart, although the London Atlas has not been widely tested for skeletons that are not of European origin.

Dental histology

Developmental features within tooth enamel are now understood to result from circadian fluctuations in the activity of ameloblasts, which are cells that produce enamel. Daily cross-striations and circaseptan striae of Retzius are visible in longitudinal thin sections cut from teeth, and

Retzius striae outcrop onto the surface of teeth as fine ridges known as perikymata. These features can be counted to document crown formation times for individual teeth. Although histological studies show systematic population variation in the duration of amelogenesis, or the formation of enamel, they also confirm narrower ages for the onset and conclusion of enamel formation than indicated by radiographic data (Reid and Dean 2006). While labor intensive, enamel histology can be used to estimate age at death very precisely for skeletons of children who died prior to the end of enamel formation.

SEE ALSO: Estimating Subadult Age:
Epiphyseal Union

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Estimating Subadult Age: Diaphyseal Length

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Age estimation is the first key step in the study of archaeological subadults (juveniles, non-adults, children) in bioarchaeology (see *BIOARCHAEOLOGY*). Subadults are defined differently between researchers and can include individuals aged up to 17–19 or even 21 years. The chronological age (actual age) of skeletal subadults is generally unknown, with the exception of skeletal collections with a documented age from coffin plates. When the age is unknown, it is the biological age that is estimated. The biological age of archaeological subadults can be estimated either from dental development (see *ESTIMATING SUBADULT AGE: DENTAL DEVELOPMENT AND ERUPTION*) or skeletal development. Skeletal age can be estimated from appearance and maturation of the skeletal elements, timing of fusion, or length of long bones (diaphyseal lengths). Estimating the age of subadults allows analysis of changes in mortality and morbidity between age groups, as well as studying the effects of an adverse environment on growth (when compared with dental development) to reconstruct life histories of past subadult populations.

Estimating the age of subadult skeletons using diaphyseal lengths is less accurate than using dental development, since long bone growth is more influenced by adverse conditions such as periods of disease, malnutrition, or starvation. In addition, nutrition and infection act in synergy where children with suboptimal nutrition are more prone to contract infections, while infectious disease may lessen nutritional uptake. More importantly, height among children is variable, even if they are from the same population and develop under the same living conditions, which is evident when looking at any modern group of same-aged children. Additionally, age estimation from diaphyseal lengths will be less accurate the

older the subadult, especially when approaching puberty. During puberty, sexual dimorphism increases due to differential hormone secretion, and this results in dissimilar adolescent growth spurts between the sexes, with girls completing their growth (fusion of epiphyses) up to two years earlier than boys. Therefore, estimating age from diaphyseal lengths is less precise than dental age and carries a greater error range, especially for older subadults (i.e., in the pubertal years). Despite these issues, estimating age from diaphyseal lengths is still useful when working with subadult remains, as there will always be cases where there is no dental information available due to taphonomy or fragmented remains. In cases with commingled remains (see *COMMINGLED HUMAN REMAINS*), diaphyseal lengths can be used as an age indicator to establish relationships between dispersed subadult parts.

Estimating age from diaphyseal lengths requires the length of the diaphysis to be compared with a known standard or an established method such as table data or regression equations. Scheuer and Black (2000) compiled several known standards of table data. The table data were predominantly derived from radiographic images from children living in the mid-twentieth century. The issue with applying such data to archaeological subadults is two-fold. Firstly, there is a difference in growth patterns between a modern population and those of an archaeological population. Secondly, a bias arises from differences in methodology when applying measurements from radiographic images to those of archaeological dry bone due to image magnification and shrinkage of dry bone. In addition, the individuals from the table data (Scheuer and Black 2000) were generally healthy, whereas deceased archaeological subadults may well have experienced compromised growth.

More recently, methods for estimating age from diaphyseal length have been explored and are generally presented in two forms: cross-sectional studies on archaeological material of known age (i.e., documented age from coffin plates), and cross-sectional studies on

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archaeological material of estimated age. Both types of study generally present their method as regression equations. Regression equations can be used to calculate a predicted age based on the measurement of the length of long bones. The advantage of using a documented sample of known age and sex is that the developed method will have a known accuracy. However, there are a limited number of subadult skeletal collections of documented age, and these tend to date from the eighteenth, nineteenth or twentieth centuries. The disadvantage of methods devised on this more recent material is that they might not be transferrable to older archaeological populations or those from geographically distant populations. This is due to discrepancies between chronological and skeletal age between populations, as well as different growth opportunities. The advantage of using methods devised on archaeological materials of estimated age is the possibility of larger sample sizes (depending on the time period), as well as the methods being population-specific and contemporaneous to the archaeological remains being investigated. The disadvantage is that the accuracy of the method is unknown. Using table data from modern children as referenced in Scheuer and Black (2000) raises the issue of “biological mortality bias” where growth data from living healthy subadults (survivors) is unlike to represent growth of subadults that died prematurely with potentially compromised growth due to malnutrition and disease. Therefore, methods developed from a modern population of subadults (survivors) would be inappropriate to use for an archaeological population of deceased subadults. Hence, when choosing a method for archaeological material, it should reflect the population under investigation in environmental conditions, time period and geography. It can therefore be from archaeological subadults of

either known or unknown age, depending on the history of the population being examined.

Future directions for estimating age from diaphyseal lengths may derive from development of newer reference data from cross-sectional studies using CT images of clinical data. However, such studies will not circumvent the problem of using aging methods developed on subadults from distinctively different environments and time periods to estimate the age of archaeological material. Therefore, data from present-day material would mainly be applicable to forensic cases rather than archaeological material.

SEE ALSO: Estimating Subadult Age: Dental Development and Eruption; Malnutrition; Osteology

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Estimating Subadult Age: Epiphyseal Union

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Whether the age at death is estimated for a single individual as part of a biological profile, or for a group of individuals seriated against each other, the estimation of the age at death from subadult skeletal remains (all individuals that are still undergoing the biological processes related to growth and development) is a routine part of skeletal analysis for bioarchaeology, paleodemography, and forensic anthropology. Using epiphyseal union is one of the primary techniques used to estimate the age at death of subadult remains, the others being dental development and eruption, and long bone growth.

Generally, all bones grow and develop through intramembranous or endochondral ossification, with some elements using both mechanisms (Scheuer and Black 2000). Intramembranous ossification involves bones growing and developing within a mesenchymal membrane (e.g., the bones of the cranial vault, such as the parietal), while endochondral ossification involves bones growing and developing from a cartilaginous model (e.g., the femur). Both mechanisms of bone growth rely on ossification centers, or areas from which bone is deposited and remodeled as it grows. The concept of epiphyseal union is primarily used for assessing the completion of various areas of bone growth using the postcranial bones (i.e., all bones except those found in the skull).

Most of the postcranial bones in the human body grow and develop from primary and secondary ossification centers. The primary ossification center serves as the main platform or structure of the bone, while the secondary ossification centers, or *epiphyses*, serve as peripheral areas of bone growth. Using the femur as an example, the primary ossification center is located in the femoral diaphysis, and there are four secondary ossification centers which are

found at the femoral head, greater trochanter, lesser trochanter, and distal end of the femur (Scheuer and Black 2000; Figure 1). When ossification centers fuse together, they form a single bony structure; this unity of ossification centers is referred to as *epiphyseal union* and reflects the end of a particular growth process, with different epiphyses uniting at different ages. Generally, ossification centers serve as the main areas of bone growth and development during the fetal, infant, and childhood periods, while it is the junctions between the primary and secondary ossification centers (i.e., growth plate or physis) that account for interstitial bone growth, and associated increases in bone length and stature during childhood and adolescence (Scheuer and Black 2000).

Most epiphyses unite between the ages of 10 and 25 years, making epiphyseal union a reliable method for estimating age for individuals in adolescence or young adulthood. While there have been a large number of investigations regarding the growth and development of the human skeleton and epiphyseal union, perhaps the earliest detailed examination of epiphyseal union was performed by Flecker (1942). However, it was not until 1957 that McKern and Stewart published their seminal work relating to age-at-death estimation from epiphyseal union. In this work, McKern and Stewart (1957) systematically analyzed identified male deceased United States military service members from the Korean War. In their publication, McKern and Stewart defined five stages (e.g., 0–4) of epiphyseal union and presented tables with the timing of each stage for most major epiphyses in the human body for male individuals aged 17–24+ years. This study was followed by many others including Webb and Suchey (1985), who investigated the epiphyseal union of the iliac crest and medial clavicle using a large sample of identified female and male individuals from the Los Angeles medical examiner's office, providing standards for the epiphyseal union of these areas for individuals with ages ranging from 11–40 years of age. In 2000, Scheuer and Black published *Developmental Juvenile Osteology*, a detailed and

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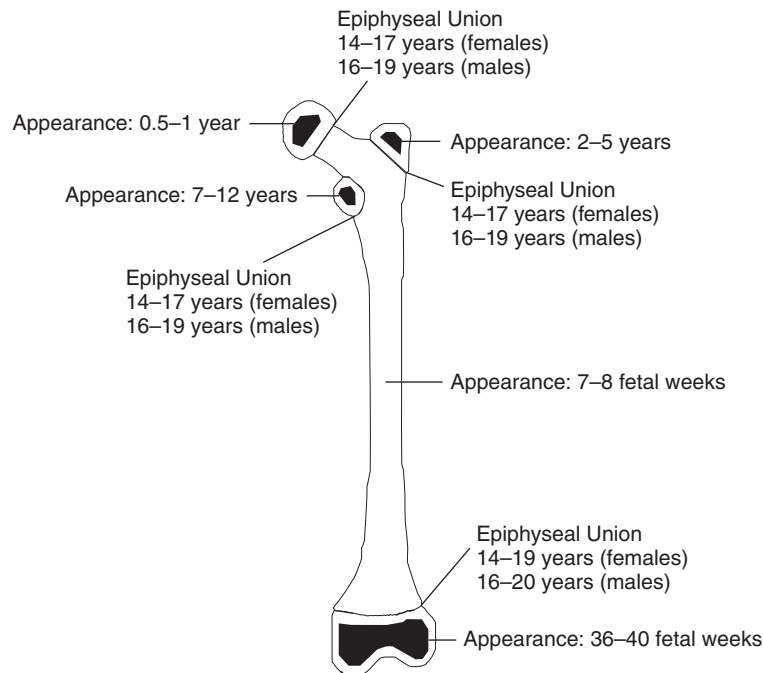


Figure 1 Diagram of human femur, with approximate ages of ossification center appearances and epiphyseal unions. Diagram altered from Scheuer and Black (2000), published by Academic Press, with updated ages from Schaefer, Black, and Scheuer (2009, published by Academic Press).

well-illustrated reference work compiling growth and development standards, including those for epiphyseal union for all the bones in the human body. In 2009, Schaefer and colleagues presented an updated and truncated version with simplified tables of epiphyseal union for females and males.

The process of initial union to final epiphyseal closure may last several years. Because of this, most methods for assessing epiphyseal union use a scoring system that evaluates the degree of union on an ordinal scale from no union present to complete union. Generally, epiphyseal union begins in the center of the epiphyseal junction and radiates out from there. Therefore, the process of epiphyseal union is typically scored based on the presence and extent of the epiphyseal line, which is a distinct area visible between the two components (typically the primary and secondary ossification centers) and tends to obliterate through remodeling over time. While the estimation of age from epiphyseal union can be performed using radiographs or dry bones, methods developed on one type of material

(e.g., radiographs) may not be directly applicable to another based on differences in observable features and scoring systems; thus validation of method application between analytical materials should always be performed prior to use.

The timing of epiphyseal union between males and females is different, representing differences in growth and development primarily related to puberty and the development of secondary sexual characteristics and the adolescent growth spurt. Additionally, it is important to remember that while the timing and sequence of growth and development processes are fairly rigid due to our evolutionary history, small yet significant differences in the timing of epiphyseal fusion have been found between different populations (Langley-Shirley and Jantz 2010). While much of this variation is due to differences in nutrition, activity, socioeconomic status, and/or secular changes, it means that methods developed on one reference sample should be applied with caution to populations with different life histories.

SEE ALSO: Bioarchaeology; Estimating Subadult Age: Dental Development and Eruption; Estimating Subadult Age: Diaphyseal Length; Osteology; Paleodemography

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Food Residue Analysis

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Residues resulting from the processing, storage, and/or consumption of food in the past can be preserved in the archaeological record in a variety of forms. Very rarely, in-situ vessel contents may be preserved, such as wooden vessels containing “bog butter” or sealed containers with the contents still held within. More frequently, visible traces of food residues may be found in association with artifacts, preserved usually through carbonization. This includes deposits adhering to cooking pots, resulting from the burning of foodstuffs during cooking. Finally, and most widespread, are nonvisible traces of foodstuffs that may be protected and preserved in association within an archaeological matrix such as ceramic or stone artifacts. Useful biomarkers (biological markers) from such residues can be very well preserved under favorable conditions, but their presence would not be detectable with the naked eye.

The origins of amorphous organic food residues can be determined using a variety of analytical techniques (see CHEMISTRY IN ARCHAEOLOGY and CHROMATOGRAPHY AND ARCHAEOLOGICAL MATERIALS ANALYSIS). All rely upon the same principle, that of identifying one, or a suite of, diagnostic biomarkers that can be unambiguously related to a source. Some of the most widely preserved organic compounds may be ubiquitous in origin. However, careful assessment of the entire composition of potential sources, which takes into account predictable degradative and post-depositional processes, can lead to the identification of diagnostic “fingerprints” based upon the survival of unique markers or distributions of markers.

Organic foodstuffs are comprised predominantly of lipids, carbohydrates, and proteins in varying proportions. The survival of these different classes is not equal; in general, the

hydrophobic (not water soluble) and relatively recalcitrant nature of lipid molecules (fats and oils, including fatty acids, waxes, and sterols) means that these survive widely, especially when protected within a ceramic matrix, although variability will be dependent on localized environmental and climatic conditions. Carbohydrates, including simple sugars and polysaccharides (e.g., starches), are more susceptible to leaching, mobility, and loss within the soil profile. Ancient proteins, while relatively soluble in water, have exceptionally been identified, primarily through immunological techniques, and, more recently, through larger-scale (proteomics) approaches using mass spectrometric methods to residues from artifacts and dental calculus using tandem mass spectrometry.

The earliest investigation of the origins of preserved lipids from organic food residues dates back to the 1970s when Condamin and co-workers investigated the fatty acid composition of extracts from Roman amphora from the Mediterranean using gas chromatography–mass spectrometry (see GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS)) (Condamin et al. 1976). While this approach was in its infancy, the distribution of fatty acids led the researchers to attribute these residues to olive oil (see OLIVES AND OLIVE OIL). In the early 1980s, Morgan et al. (1983) investigated the fatty acid composition of “fatty materials” from a Thule settlement in northwest Canada, drawing comparisons with fatty acid compositions of modern marine mammal fats. This study highlighted that the highly unsaturated fatty acids, present in modern marine fats, were absent from the archaeological residues and, hence, a fundamental principle of the study of ancient food residues: that various degradative processes, such as thermal degradation, microbial activity, and leaching, need to be anticipated, and accounted for, before archaeological biomolecules can be assigned to a potential source.

Since these early studies, considerable research has been performed to better understand the degradation pathways of lipids in food residues

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undergoing cultural processes such as heating, as well as processes arising post-depositionally. This has confirmed not only the loss of more unstable components such as unsaturated fatty acids but also the transformation of labile lipids to more stable degradation products that may have significant interpretative value. Thus, for example, distinctive distributions of mid-chain ketones are now understood to form through the heating of animal fats within a ceramic matrix, while a series of relatively stable markers arise from the thermal degradation of polyunsaturated fatty acids characteristic of marine fats and oils (see Roffet-Salque et al. 2016 and references therein).

The fingerprints of lipids from food residues can differentiate foodstuffs originating from a variety of sources, including animal fats, plant epicuticular (surface) waxes, plant oils (see OILS AND FIBERS), and insect waxes (i.e., beeswax, associated with honey exploitation). Fats originating from animal products are usually most widely recovered, likely due to not only the widespread cooking or processing of animal products, but also their relatively high lipid content compared with other types of food products. Lipid distributions characteristic of degraded animal fats can be relatively distinctive, comprising saturated fatty acids and characteristic ranges of triacylglycerols (triglycerides) and their degradation products. However, assigning these fingerprints more specifically to their origins usually relies upon the determination of the stable carbon isotope composition of the major fatty acids that are preserved. This stable isotope signature records the metabolic and dietary origin of the carbon and therefore can be used to discriminate between animal fats of ruminant and nonruminant origin (e.g., separating cattle, sheep, and goats (see SHEEP AND GOATS) from pig (see PIGS) or horse, and terrestrial from marine or freshwater species. Importantly, differences in the biosynthesis of fatty acids in the mammary gland of ruminants means that fats of dairy origin can also be separated from carcass (meat) fats from the same species. This approach has enabled large-scale questions regarding the origins and timing of animal secondary products exploitation (e.g., see Roffet-Salque et al. 2016 and references therein) to be targeted (see DOMESTICATION AND DAIRYING). Currently, the separation of fats from different species within ruminant groups is

challenging; however, the composition of exceptionally well-preserved triacylglycerols using nanoelectrospray ionization mass spectrometry (see MASS SPECTROMETRY (MS)) has shown the ability to distinguish fats from cattle, sheep, and goat (Mirabaud, Rolando, and Regert 2007).

Lipid residues of plant food origin are somewhat less widely recovered, but include long-chain aliphatic compounds originating from plant leaf waxes, as well as phytosterols and terpenoids. Plant oils, characterized by higher abundances of unsaturated fatty acids and phytosterols, have been identified from culinary and other contexts (e.g., used in mummification or lighting). Some types of plant oils, such as date palm oil, Brassicaceae (including mustard, radish, and rapeseed) oils, and castor oil, have unique or unusual markers, enabling a relatively specific identification of origin. However, others, such as olive oil, are not yet known to possess sufficiently specific markers that will survive over archaeological timescales. Wax from bees has a distinctive and recalcitrant distribution of *n*-alkanes, *n*-alkanols, and palmitate wax esters. Through tracing of beeswax residues preserved in ancient pottery, the paleoecological spread and exploitation of honeybee products by Old World agriculturalists has been demonstrated (see Roffet-Salque et al. 2016 and references therein).

While possessing the potential to provide a higher level of species-specific identification, protein residues from cooking, killing, or butchery of resources have posed significant challenges to identify in practice. Considerable doubt has been cast upon the identification of blood proteins adhering to lithic artifacts based upon hemoglobin crystallographic techniques or immunological reactions, due to a lack of reproducibility, contamination, and, for the latter, cross-reactivity, producing findings at significant odds with the archaeological and environmental context. The analysis of archaeological protein residues from pottery vessels has also been challenged by not only seemingly rapid degradation and hydrophilicity, but also apparently limited transfer of proteinaceous material into the clay matrix (Evershed and Tuross 1996) and/or difficulties extracting molecules that appear to be strongly bound to a mineral surface such as ceramic (Craig and Collins 2002). A

novel digestion-and-capture extraction technique followed by immunological analysis using a monoclonal antibody raised against bovine α -casein has been developed, enabling positive extraction and identification of ancient milk proteins from archaeological sherds and ethnographic dairying pots, which were not detected in negative controls (Craig et al. 2000). More recent approaches to identify archaeological proteins employ shotgun proteomics using liquid chromatography–tandem mass spectrometry. This has so far detected the whey protein β -lactoglobulin trapped in ancient human dental calculus widely among dairying populations, but found it only at low prevalence or absent in societies with a low or declining history of dairying (Warinner et al. 2014).

Carbohydrates, or saccharides, include highly soluble simple sugars through to complex polymeric molecules such as starch and cellulose. Starches, although insoluble in (cold) water, are susceptible to enzymatic attack, which breaks them down into their water-soluble sugars, and therefore they readily degrade in the burial environment. However, in protective conditions such as small cavities in stone tools or grindstones, starch granules (see STARCH GRANULE ANALYSIS) may survive over archaeological timescales, and ancient processing of cereals, roots, and other plants has been identified archaeologically, based upon morphological characteristics shared with modern specimens. Although more specific identifications have been reported, identification beyond genus level is usually not achievable through this approach. Heating of starch during processing (i.e., cooking) will initiate gelatinization, with retrogradation upon cooling resulting in an enzymatically more stable, but morphologically altered, structure. The effects of diagenetic alteration upon the morphological state of ancient granules must therefore be taken into account. With wider concerns regarding the possible contamination of archaeological artifacts with modern starch granules, recent attention has turned to starch trapped in ancient dental calculus as a protective and contextually secure matrix preserving biochemically unaltered starch granules (Hardy et al. 2009).

SEE ALSO: Diet and Carbon Isotopes; Isotopes

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Genetics: Ancient

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Characterization of human genetic variation has expanded our understanding of human history and evolution in recent decades, providing a unique perspective in understanding past demographic processes. Applying genetic analysis to the remains of once-living organisms can obtain information directly from the past. Thus, we now have a direct tool to reconstruct specific patterns of genetic variation among past populations and are able to understand the patterns within the context of the sociocultural, historical, and environmental settings informed by archaeological data.

DNA analysis targets specific regions of the nuclear and mitochondrial genome. The majority of biological functions are governed by genes on the nuclear DNA. The nuclear genome consists of more than three billion nucleotides that are organized in 23 pairs of chromosomes, including the sex chromosomes X and Y (see *CHROMOSOMAL DNA*). However, mitochondrial DNA (mtDNA), a separate genome of the cellular organelle mitochondrion, has a higher copy number than nuclear DNA and has become an important source of genetic analysis applied to archaeological contexts (see *DNA: MITOCHONDRIAL*). While the nucleus exists in a single copy per cell, there can be as many as a few dozen mitochondria, which translates into a greater likelihood of success when amplifying specific DNA regions from archaeological specimens.

More than 30 years ago, publication of a mitochondrial DNA sequence from the extinct quagga, a subspecies of the plains zebra, ushered in the field of ancient DNA research. The invention of polymerase chain reaction (PCR) further propelled the field, allowing fragmented DNA molecules from organic specimens to be copied a million fold. Once a sequence was obtained from ancient remains, it became possible to make

comparative analyses with the larger population or species. The earliest ancient DNA studies focused on extinct specimens, primarily to understand evolutionary processes. Soon after, studies applied genetic analysis to hominin remains, such as Neandertals, revealing new information on human origins and adaptations. Specific genetic variants involving speech and pigmentation identified from Neandertal remains present information on modern human-specific adaptations. Other genetic variants have been implied in various medical conditions. Now more recent technologies are exploring genetic contributions from ancient hominins to modern humans, such as studies of the remains from the Denisova Cave (see *DNA: NEXT GENERATION SEQUENCING*).

Ancient DNA analysis can address a range of archaeological questions. One significant contribution of ancient DNA analysis is to enhance bioarchaeological investigations seeking to provide information regarding an individual's biological and cultural identity and affinities. An individual's sex can be identified by targeting a sequence on the amelogenin gene present on the X and Y chromosome. DNA identification of sex may either complement the osteological analysis or provide information when the skeletal data is unavailable. Additional markers on the nuclear DNA allow a genetic profile similar to that used in forensic investigations, so that not only can individuals be identified among commingled remains but familial relations may be elucidated in a burial context and genetic ties between the remains and living descendants may even be revealed. In the absence of nuclear DNA, the maternally inherited mtDNA can also clarify genetic relations, albeit at a deeper ancestral level instead of closer familial ties. Without a doubt, information regarding genetic relations can address broader questions concerning the social organization of past populations including aspects of kinship, descent and lineage, and marriage patterns.

As mtDNA represents ancestral maternal lineages and can reveal population patterns at a deeper time scale, ancient mtDNA studies seek to

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explore demographic processes involving genetic continuity and examine patterns of genetic affinities and variation across broader geographical regions. The Mesolithic–Neolithic transition in Europe has been characterized by a distinct genetic pattern between hunter-gatherers and agriculturalists based on the analysis of human remains from the region. Ancient DNA studies have examined genetic continuity after the collapse of the Andean Wari empire and have revealed patterns of specific demographic processes of the Vikings. Studies have also illustrated genetic patterns associated with ancient expansions of specific cultural or linguistic groups in North America, such as the Numic-speaking Native American groups in the Great Basin. Genetic analysis of historical human remains from burials and cemeteries have provided another dimension to the sociopolitical processes involving the African diaspora and the American slave trade by using genetic affinities to populations from specific geographical regions.

Genetic analysis of past populations can also contribute to the discussion of health and disease patterns. Lactase persistence, the ability to breakdown lactose in milk after childhood, is a genetic trait that is absent in most mammals. Among humans however, the frequency of lactase persistence reaches 70–80 percent in some populations. The origin of the genetic variants responsible for lactase persistence is currently debated but has been associated with the advent of dairying practices since the trait is more common among populations with a long history of dairying (see DAIRYING). Ancient DNA analysis of human remains from the earliest agricultural groups to remains from the medieval period is revealing a rapid selection process for the trait (Krüttli et al. 2014).

Paleopathological studies based on osteological analysis have been central to understanding the morbidity and mortality of past populations (see PALEOPATHOLOGY). Genetic analysis has allowed the possibility to identify genetic diseases among past individuals such as thalassemia. Infectious diseases are caused by different types of pathogens each with unique characteristics and adaptations. Many pathogens have a long history of coevolution with humans and have left a substantial mark on human history. Differential diagnosis of skeletal pathology can be

quite difficult from lesion morphology alone (see DIFFERENTIAL DIAGNOSIS). Ancient DNA analysis successfully identified certain bacterial diseases, such as tuberculosis, from human remains. Caused by a cluster of bacterium species known as the *Mycobacterium tuberculosis* complex, tuberculosis has been the most successfully identified pathogen from human remains. Studies have shown the evolutionary history of the disease in the Americas and Europe (Harkins and Stone 2015). Other diseases, including leprosy caused by *Mycobacterium leprae* and the bubonic plague caused by *Yersinia pestis*, have also yielded DNA from human remains. Further whole genomic analysis is revealing phylogenetic information about the various strains that has implications for modern epidemiology and pathogen evolution (see GENOMICS: ANCIENT).

Genetic analysis has also been utilized to trace the origins and spread of domestication of plants and animals by distinguishing wild and domesticated species and by characterizing the variation obtained from various archaeological contexts. While the origin of domesticated wheat grains, such as emmer (*Triticum dicoccum*), einkorn (*T. monococcum*), and spelt (*T. spelta*), is not clearly resolved, genetic analysis has been utilized to distinguish wheat species from charred archaeological remains and to trace the dispersal of wheat cultivation. As a principal domesticate crop of the New World, DNA analysis of maize (*Zea mays mays*) remains show two separate expansions of the crop from Central America into South America (Freitas et al. 2003). Crop origins and their dispersals have also been characterized for domesticates including rice (*Oryza sativa*), potatoes (*Solanum tuberosum*), beans (*Phaseolus vulgaris*), and grapes (*Vitis vinifera*). Ancient DNA analysis of wild and domesticated bovine (*Bos taurus*) and swine (*Sus scrofa*) remains have revealed a process of dispersal linked to the cultural interaction of different groups from their origins in the Near East across Europe. Genetic investigation of the domestic dog (*Canis lupis familiaris*) shows a complex process of domestication that possibly occurred in multiple regions. Any ancient DNA analysis is based on understandings of modern variation and in order to discern wild and domesticated plants and animals, information on modern genetic variation becomes even more crucial.

Recent genetic studies have utilized a wide range of organisms to understand past human environments. While early studies were most successful at obtaining DNA from bone specimens, recent developments have extended the types of samples for DNA analysis. Ancient DNA research is not necessarily restricted to vertebrates, but can include arthropods, worms, a range of plant components (wood, pollen), and various microorganisms. DNA can be deposited by an organism's skin flakes, urine, feces, eggshells, and saliva. These traces of DNA have been obtained from a variety of environments including lake cores, surface soils, and cave sediments that allows data regarding past biodiversity and the environmental settings that past humans inhabited (Pedersen et al. 2015). The importance of human environments is central to the study of human microbiomes, referring to the collection of microbial genomes present in humans. The composition and variation of microbiomes among human populations have been implicated in health and diseases, and analyses from human remains are providing novel insights into the diet and broader ecological environments of past societies (Warriner, Speller, and Collins 2015). Current research analyzing RNA transcripts, processed copies of DNA segments, from ancient maize kernels may further shed insight on the external environmental conditions of domestication. Research on the methylation of DNA in ancient specimens may provide yet another window into understanding epigenetic changes that underlie crucial developmental processes, which are also implicated in diseases among humans (Smith, Monroe, and Bolnick 2015). Expanding the scope of specimens for DNA analysis can broaden the types of research questions addressing the lives of past populations and allow for fruitful collaborations among a wide range of specialists within and beyond the archaeological sciences.

Techniques for sequencing and extracting low quantities of DNA from degraded specimens continue to improve, extending the limits regarding the age and quality of information obtained. Nevertheless, limitations still exist relating to the cost of analysis and factors of DNA degradation. Degradation of DNA occurs after the organism's death and continues from in situ to post-excavation, influenced by temperature,

water, oxygen availability, and microbial activity among others. It remains difficult to obtain autosomal data or STR profiles to infer familial relations within a burial context, and when mtDNA data is available one must understand that the genetic relations inferred come from a maternal ancestor shared by thousands of people. Still, the development of techniques for ancient genetic analysis will continue to push the boundaries for the type of questions we can now ask from the archaeological record.

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Genomics: Ancient

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The study of genetic material from archaeological contexts is a relatively recent field; however, our ability to illuminate the past in a variety of new and interesting ways has made genomics a dynamic component of archaeological science. During the past 30+ years of ancient DNA (aDNA) study, technological advancements have allowed researchers to go from merely identifying the presence of DNA and RNA, to being able to characterize the entire genome of past humans and hominins. The genome is the complete genetic code found in the cells of an individual, organized into long strands known as chromosomes. Genomics is defined as the field of study in which we look at the whole genome of an organism, rather than individual loci or genes. Growing out of the fluorescence in related fields such as biology and chemistry, genomics has seen significant advances and foibles, but recently has allowed for a variety of insights into the genetic history of archaeological material that would have been impossible only a few years ago.

After death, the mechanisms that control DNA repair in cells cease to function, leading to a variety of breakdowns in the strands of base pairs that comprise our chromosomes and mitogenome (the small, circular piece of DNA housed in the mitochondria of the cell). These nucleotide bases (adenine, cytosine, guanine, and thymine, often abbreviated as A, C, G, and T) form the code that is the genetic basis of our bodies. As DNA decays, the long chains of nucleotides break down into shorter and shorter pieces, often linearly with time. Additionally, the nucleotides themselves can break down, along with a variety of other issues (Fulton 2012). These problems make aDNA difficult to work with, and sometimes even impossible to recover, although many recent advances have aided in making previously impossible samples now viable for analysis. Preservation

of endogenous and accessible aDNA varies widely from site to site, depending on the microenvironment of the soil and conditions of each burial. Typically, higher latitudes and colder environments, with less temperature fluctuation, allow for higher success rates.

Source material

The first studies in the field focused on mummies and other dried tissue (Pääbo 1989); however, it soon became clear that this was a poor source of endogenous DNA because mummified tissues are often contaminated. Skeletal remains are now the most frequently used. Continued research has explored which parts of the skeleton contain the highest amount of endogenous DNA. This has often led to tooth root sampling and, more recently, the drilling of the petrous portion of the skull (Hansen et al. 2017), which appears to carry the highest surviving amount of genetic material.

Ancient DNA has also been recovered from materials such as coprolites (preserved fecal material), quids (chewed plant material), menstrual aprons (LeBlanc et al. 2007), stone tools, and even the very soil in which an individual was buried. Additionally, researchers have used nonhuman sources of genetic material to address questions ranging from human occupation, domestication, and climate change. These novel sources of aDNA will continue to receive attention as researchers look for ways to avoid the destruction of human remains. Moreover, analyses of coprolites and masticated materials allow one to look at the microbiome of the individual—the bacteria inhabiting individuals.

The desire to avoid working with human skeletal material is a growing concern, particularly Native American remains in the United States. While collaboration between geneticists and Native Americans can potentially lead to a better understanding between the two groups (Rasmussen et al. 2015), more needs to be done to help bridge the gap between scientists and Native

communities in order to foster understanding on both sides.

Extraction and analysis

Protocols for DNA extraction vary, but the laboratory itself is a tightly controlled environment. The risk of contamination from modern samples or researchers can be high, as modern DNA can overpower (outcompete) results from that of the sample due to its higher copy number and less damage. These laboratories maintain strict access, cleaning, and other methods that ensure that the amount of contamination introduced to the sample is kept to a minimum. Negative controls are also utilized, allowing for the potential detection of the introduction of foreign DNA to the extraction.

After the aDNA has been extracted from the sample, it can be analyzed in a variety of ways. Some of the original studies used enzyme digests (restriction fragment length polymorphisms (RFLP)), which help to identify notable nucleotide polymorphisms. As methods improved, direct sequencing of the nucleotide bases was carried out, allowing researchers to identify regions of interest within the genome. In particular, single nucleotide bases that differ (single nucleotide polymorphisms (SNPs)) are often focused on to look at individual and population diversity. The advent of next generation sequencing (NGS) has made genomic-level analyses possible. These newer methods, such as the Illumina sequencing platform, have allowed for massive amounts of data to be accrued, permitting whole genomes to be sequenced.

The data that result from NGS platforms are in the form of thousands of short strings of base pairs, known as reads, the length of which varies from less than a hundred base pairs to several hundred. These reads are mixed together and in no particular order, requiring the computational skills often found in the field of bioinformatics. The data are analyzed to remove potentially misread bases or other errors, and also to separate out multiple extractions that were mixed together and can be identified through unique tags added to the DNA through indexing in the preparation process (known as library preparation).

From this, the DNA must be reassembled into the patterns of base pairs that are found in the individual chromosomes or mitogenome of the individual sequenced. This reassembly process is done through software that compares the small fragments of DNA sequence and lines them up against a known, similar sequence. If the species is unrelated to any known comparable species, the *de novo* sequence assembly can still be completed; however, more care must be taken. Due to the data output of NGS, there may be many small DNA fragments that sequence the same base pair locus when all are aligned against one another. This is the concept of coverage, wherein the more times every base pair in the consensus sequence is sequenced, the more confidence one can have in the base being accurate. Should errors or mistakes in sequencing or contamination from an outside source be present in the sample, this would be revealed as a mix of different bases at a locus that are not in agreement. This must be fixed, or taken into account in statistical analyses (such as a low contamination rate being found in ancient genomes). The end result of these analyses is the targeted DNA of interest in the study, which is a long string of base pairs composed of multiple underlying sequence fragments. The more times an individual base pair is sequenced (covered), the stronger the confidence in the data.

Once the genome has been assembled, the type of analysis carried out will vary depending on the study. For example, genomes can identify gene regions, which can aid in understanding variants between individuals and species that may not be captured by looking at only polymorphisms known to exist in one population or species. This ascertainment bias leads to focusing on mutational markers that are found in one group but not necessarily another, which can skew findings as the diversity in one population cannot be captured by the diversity of another.

Applications

The increase in genomic data has led to better understanding the evolution of modern humans. The ability to look at the genome as a whole is beneficial for a variety of reasons, the first being that it allows one to look at a person's maternal

and paternal ancestry bilaterally (and therefore familial relationships). By contrast, uniparental markers (like mtDNA and Y-chromosomes) discern ancestry from only one side. Genomics allows one to document more in-depth relationships between individuals at a single site, and between populations. These can aid in understanding migratory behavior, marriage patterns, and many more anthropologically important topics.

The second large benefit of genomics data is that the data allow for understanding the selective pressures on human populations. These range from the selection for lactose tolerance (Sverrisdóttir et al. 2014), to skin pigmentation (Wilde et al. 2014), disease, and many more. Through specialized analysis, it is possible to see how natural selection, the environment, culture, and other species have all played a role in shaping our genome. The extended benefits of genomics research in archaeology are unfolding, with many more to come.

Ancient DNA has also opened doors into understanding our relationship with other hominin species. Some of the most spectacular results have come in the form of aDNA recovered from remains of *Homo neanderthalensis* and from the remains found at the Denisovan cave in the Altai region of Siberia, Russia. From these findings we can see how we are related to early hominin species, how we interbred with them, as well as selective forces that acted to retain mutations from these other species in our modern human genome.

Many more regional topics have also been investigated through the use of ancient genomics. For example, the peopling of the Americas has long been of interest archaeologically, and through the use of aDNA it has been possible to better understand when and by what route people populated the continents (Bolnick et al. 2016). At a local level, studies within archaeological sites have successfully addressed questions of how individual skeletons were related, such as the identification of maternally related individuals interred in the same room in Chaco Canyon (Kennett et al. 2017).

SEE ALSO: Bioarchaeology; Chromosomal DNA; DNA: Mitochondrial; DNA: Next

Generation Sequencing; Estimating Skeletal Sex: Metrics; Ethics in Conservation; Genetics: Ancient; Paleoethnobotany and Ancient DNA Analysis; Zooarchaeology and Ancient DNA

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Human Growth and Development

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There is now a well-established scholarship on the bioarchaeology of children, ranging from early works that introduced the osteology of children (Cunningham, Scheuer, and Black 2016), to anatomy manuals for forensic and archaeology practitioners, to volumes devoted to the evolution, biocultural significance, and interpretation of the life and death of subadults in skeletal and living populations (Lewis 2009). A useful theoretical approach to organize the study of subadults is to consider the human life cycle as composed of different bioculturally defined stages (infancy, childhood, juvenility, adolescence, adulthood) (Bogin 1999), through which subadults pass in a process of growth and development. Growth could be defined as a quantitative increase in size or mass (such as the length of long bones), whereas development could be defined as the progression of changes, either quantitative or qualitative, that lead from an undifferentiated or immature state to a highly organized, specialized, and mature state (for instance, dental eruption until functional occlusion for teeth, or size and shape changes of the epiphysis from ossification until fusion with diaphysis) (Bogin 1999). The mature state, or adulthood, would be defined as being a “functionally mature individual.” In other words, the maturity and size of the body, as well as the social engagement and interaction of the person, change along the aforementioned biocultural stages until reaching adulthood (see *BODIES AND EMBODIMENT* and *EMBODIMENT*). The two most basic steps on which subsequent analysis of subadult remains rely are the estimation of sex and age-at-death, placing the individual within one of these developmental stages. Then, the study of growth and maturation presents a broad picture of the living conditions of subadults,

increasing our knowledge of the structure and dynamics of past societies.

Sex estimation and juvenile remains

Research on sex estimation has moved from qualitative assessment of pelvic and cranial traits and classic metric dimensions (permanent canine crown diameter) to 3D analysis of shape (see *IMAGING IN HUMAN REMAINS*), offering some improvements in the understanding of the development of sexual differences in the skeleton. However, due to the fact that most of the skeletal sex differences in adult size and shape develop from the adolescent stage onwards (in parallel to secondary sexual development), no reliable method for the estimation of the sex of subadults based on morphological observations is currently available. The definitive tool for sex determination in younger ages is the genetic analysis (see *CHROMOSOMAL DNA AND GENETICS: ANCIENT*), still of limited use due to its invasive sampling, need of laboratory infrastructure, and cost. The lack of a reasonably accurate, and straightforwardly applicable, method for sex estimation of subadult remains results in an important loss of information for the biocultural reconstruction of the lives of, at least, preadolescents.

Juvenile age-at-death estimation: biological and chronological age, and within-population variation

In the estimation of the age-at-death of subadult remains, it is first important to understand the difference between biological age and chronological age. Biological age (BA) estimation was originally devised for comparison with chronological age (CA) in pediatric studies, in order to ascertain the degree of delay or advance in maturation of a particular child in comparison with reference data for healthy children, and not for pinpointing CA (Cameron and Bogin 2012). The basic assumption of the methods available to assess BA is that

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for living, healthy human children, juveniles, and adolescents, CA and BA are highly correlated and one year of CA advancement will equal one year of BA advancement. It is also important to note the normal within-population variation in the relation between BA and CA, which can be considered as a measure of the biological resolution of these methods. As recently stated, “Invariably the spread of actual ages around any particular maturity indicator and/or the spread of maturational ‘ages’ around any particular chronological age are of the order of ± 2 years” (Cameron 2015). When an age-at-death is estimated for a subadult skeleton, we are currently extrapolating a CA from a BA. There are three broad categories of BA, namely dental, skeletal, and somatic, whose use in age-at-death or CA estimation of subadult remains is reviewed here.

The most widely used method for CA estimation of subadult remains is the estimation of dental age, based on the simultaneous assessment of tooth formation and eruption in the so-called dental charts, the Schour and Massler, Ubelaker and London atlases being the most commonly used (Cunningham et al. 2016) (see ESTIMATING SUBADULT AGE: DENTAL DEVELOPMENT AND ERUPTION). This qualitative approach can be complemented by the metric study of developing teeth.

The assessment of skeletal age can also be used for CA estimation, mainly in terms of degree of fusion between ossification centers (see ESTIMATING SUBADULT AGE: EPIPHYSEAL UNION). One of the problems of this approach is the scarcity of accurately known sex and age skeletal collections of subadults (the most widely known being Lisboa and Coimbra in Portugal, Granada in Spain, Spitalfields and St Bride’s Church in the United Kingdom, Bologna in Italy, Haman-Todd in the United States, and Dart in South Africa), with limited sample sizes especially from two to three years onwards. Small sample sizes result in a limited knowledge of the normal variation in bone maturation, although the above-mentioned interval of ± 2 years of variation between BA and CA for the most used pediatric methods should be always considered. Further complications when using subadult documented collections come from differences in bone maturation between populations (addressed below), and from the representativeness of the

growth and maturation of these children in relation to the population at large (the survivors). The solution has been to combine data from different documented collections and increasingly study clinical data (radiographs, computed tomography (CT) scans, and magnetic resonance imaging (MRI)), a strategy that allows one to gather large, and sex-balanced, sample sizes. Results are already available for CA estimation from skeletal maturation of living samples, several of them including Bayesian statistical approaches (see BAYESIAN STATISTICS AND ESTIMATING ADULT AGE: TRANSITION ANALYSIS) (Lottering et al. 2016).

Finally, CA can be estimated from a measure of size attained, through dimensions of different bones (see ESTIMATING SUBADULT AGE: DIAPHYSEAL LENGTH), from dozens of measurements from the prenatal to early postnatal periods, to selected dimensions (generally lengths and widths) of cranial and postcranial bones for later ages. The most used measurements are long bone lengths and widths, and there are recent summaries of formulae for age estimation (Cardoso, Vandergugten, and Humphrey 2016). However, as mentioned for bone maturation, it is important to note that there might be major differences in growth between populations that limit estimation of CA from size, which are addressed in the next section.

Growth and maturation assessment and between-population variation

When we estimate age-at-death we are thus extrapolating a CA from a BA, and the normal ± 2 years within population variation should always be acknowledged. However, there is also considerable variation between populations in growth and maturation due to socioeconomically mediated differences in the quality of the environment during the subadult period (nutrition, disease, workload). Intergenerational changes towards earlier teeth formation have been observed in some populations in parallel to modernization, although other authors found no delay in tooth formation associated with sustained malnutrition, and the general consensus is that teeth present substantial biological stability to environmental insults.

Accordingly, dental age assessment is the most robust method for CA estimation. Delays in skeletal maturation have been observed associated with adverse environmental conditions, and intergenerational changes towards earlier bone maturation have been observed parallel to improved living conditions (Cameron and Bogin 2012). Finally, height-for-age (or its skeletal proxy like femoral length) is generally used as an anthropometric measure for assessment of growth status in living children (Cameron and Bogin 2012), and several studies of positive and negative temporal changes in adult stature across generations have been observed parallel to political, social, and economic changes in diverse human populations (Bogin 1999). A recent comprehensive study of a Neandertal juvenile skeleton illustrates the importance of considering all these biological and environmental factors when studying growth and maturation (Rosas et al. 2017).

A critical step in the estimation of CA from BA in subadult remains is thus the choice of the method in terms of the differences between the subadult sample under study and the child sample from which the method was developed. If our study sample and the reference sample differ significantly in the quality of the environment during the growth period, it is likely that we will under- or overestimate CA from BA, since we would be incorporating in our CA estimation the between-population variation in both samples. If we use modern references developed in middle-class to well-off samples of children, then the most probable risk is that of underestimation of CA (Lampl and Johnston 1996). This risk can be diminished when the reference sample comes from the aforementioned documented collections, since most of them come from populations of children living in unfavorable conditions which could more likely resemble that of past populations. For CA estimation, especially when using size measurements, the best procedure would be to have population-specific references, or to choose a reference sample known to show similar growth conditions to the sample under study.

In fact, taking into account the sensitivity of skeletal maturation and growth to the quality of the environment, the general strategy in bioarchaeological studies is to use dental age as the

closest estimate of CA, and then look for differences in skeletal maturation and size in relation to a modern reference as a measure of the quality of the environment of growth. This approach can be further refined by the differential growth and maturation of different skeletal systems across the stages of the life cycle, with the implication that a record of the environment during different stages is archived in different parts of the skeleton. The classical example of analysis of different teeth and/or of sections within a single tooth to obtain a chronological record of different periods of the life of the individual in terms of diet and mobility (see DIET AND CARBON ISOTOPES; DIET AND NITROGEN ISOTOPES; DIET AND SULFUR ISOTOPES; DIET AND TRACE ELEMENTS; and INFANT FEEDING) can also be expanded to growth and maturation of the skeleton. For instance, the well-known early growth and maturation of the bones associated with the central nervous system would record environmental insults during the early stages of the life cycle, while the estimation of age of initiation and completion of the adolescent growth spurt could be associated with the quality of the environment during late juvenility and the adolescence period. In this regard, a very interesting addition to the classic works on childhood is the recent research addressing the estimation of puberty in skeletal remains (Lewis 2016).

The estimation of age-at-death and the outlined biocultural approach for basic growth and maturation assessment in subadult remains constitute the basis for further dental and skeletal research. For instance, the study of pathological conditions (see PALEOPATHOLOGY) in subadult remains is an increasingly important area of research, with recent interesting contributions from trauma, and metabolic and infectious diseases (see Lewis 2018). It is only through the joint consideration of all the available osteological, archaeological, and documentary information (see BIOARCHAEOLOGY) that the full potential of subadult skeletal remains for bioarchaeology can be realized.

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Human Skeletal Geochemistry

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The field of geochemistry examines the chemical composition of the soils, rocks, and oceans of the Earth to understand the processes by which our planet was formed and has been transformed through the ages. As such, geochemists use the methods of chemical analysis to identify the physical and chemical processes that led to the formation and distribution of natural materials. The geochemical analysis of bone emerged following the discovery of radiocarbon dating, now often applied to archaeological bone. After death, the remains of all living things, including humans, enter the geological arena. The human skeleton contains a mineral structure that is part of this arena, both before and after death. Geochemical principles can be applied to understand how bone forms, its natural composition during life, and how bone undergoes changes in chemical composition after its entry into a burial context. Human behavior determines the chemicals that ultimately enter the body, and therefore, the bones. Accordingly, the chemistry of archaeological human bones can shed light on environmental, cultural, chronological, and biological aspects of past human lives.

Bone microstructure

Bone comprises both organic and inorganic components, which account for roughly 30 percent and 70 percent of the total dry weight of bone, respectively. The organic component of bone is primarily formed from type I collagen, a protein that forms the structure of many bodily tissues, including tendons, ligaments, skin, and bone. While collagen comprises roughly 90 percent of

the organic component of bone, the remainder is made up of noncollagenous proteins, lipids, and water. The isotopic composition of collagen has been used to reconstruct paleodiet via stable carbon (see DIET AND CARBON ISOTOPES), nitrogen (see DIET AND NITROGEN ISOTOPES), and sulfur (see DIET AND SULFUR ISOTOPES) isotopes, which broadly reflect the protein-based components of diet (Ambrose and Norr 1993). In addition, isotopes of carbon are used to radiocarbon date materials. Amino acid racemization is also used to date archaeological deposits.

In contrast, the inorganic component of bone is composed of mineral crystals of a calcium phosphate called hydroxyapatite, or hydroxylapatite. Hydroxyapatite is a carbonated apatite that is usually written as $\text{Ca}_{10}(\text{PO}_4)_6\text{OH}_2$. While hydroxyapatite has a defined chemical composition, it can be variable depending on interactions with other elements. Hydroxyapatite, like other members of the apatite group, has several sites where atomic exchanges can occur. Atomic exchanges of this kind occur when ions of similar size and charge substitute for one another in the hydroxyapatite crystal lattice. Most significantly, skeletal hydroxyapatite is carbonated, meaning that carbonate ions substitute for the phosphate group (Type B substitution) and to a lesser degree at the hydroxyl positions (Type A substitution), and adhere to the surface of the thin plate-like or book-like hydroxyapatite crystals (Le Geros 1981). Researchers have investigated paleodiet and paleomobility via trace element analysis (see DIET AND TRACE ELEMENTS), as well as carbon (see DIET AND CARBON ISOTOPES), oxygen (see MOBILITY AND OXYGEN ISOTOPES), calcium, lead (see MOBILITY AND LEAD ISOTOPES), and strontium (see MOBILITY AND STRONTIUM ISOTOPES) stable isotopic compositions of hydroxyapatite.

Alkaline earth elements in bone

Substantial geochemical research has focused on elements that can substitute for calcium and

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phosphorus in hydroxyapatite. Calcium (Ca), strontium (Sr), and barium (Ba) are all alkaline earth elements, which are those elements in the second column of the periodic table that share structural and chemical similarities. In the case of strontium and barium, both are positively charged, divalent atoms that are similarly sized to calcium, which allows them to replace calcium in hydroxyapatite. Sr and Ba are not metabolically regulated; instead, their levels in bone broadly reflect their abundance in the diet. Thus, researchers have used the ratios of Ba/Ca and Sr/Ca in bone to reconstruct paleodietary behavior, as well as Ba/Sr ratios to detect consumption of marine resources (Burton and Price 1990).

Strontium and barium atoms are slightly larger than calcium. In the body, this means that Ba and Sr are not incorporated into hydroxyapatite at the same rate as calcium. This process, wherein calcium is preferentially absorbed relative to strontium and barium, is called biopurification. The net result of biopurification is that the amount of barium and strontium in hydroxyapatite is less than the levels of either in the diet, such that there is a trophic level effect moving up the food web (Burton, Price, and Middleton 1999).

A variety of factors limit the analytical potential of using strontium and barium levels in bone to reconstruct paleodiet (see DIET AND TRACE ELEMENTS). There is substantial variation in both barium and strontium levels across space such that geographical differences could mask any dietary differences (Burton et al. 2003). Furthermore, the barium and strontium abundances in bone are not directly proportional to diet; instead bone Ba/Ca and Sr/Ca are disproportionately influenced by foods high in calcium (Burton et al. 1999).

Non-alkaline earth elements in bone

Although lead (Pb) is not an alkaline earth, it substitutes for calcium in hydroxyapatite in much the same way as barium and strontium, and isotopic studies have investigated mobility patterns using lead isotopes in bone (see MOBILITY AND LEAD ISOTOPES). Zinc (Zn) also occurs in bone and has received some attention in paleodietary

studies, although it does not appear to reliably reflect dietary behavior (Dolphin and Goodman 2009).

While many elements are incorporated into bone via biogenic processes, multi-element assays may also help to identify postmortem elemental exchange, or diagenesis (see DIAGENESIS OF BONE). Once deposited in an archaeological context, bone mineral interacts with the burial environment. These changes can be classified as either diagenesis or contamination. Changes to the chemical structure of the bone, involving additions to the crystal structure, loss of elements due to leaching, and substitutions of ions that occur postmortem, constitute diagenetic changes. In addition, bone may become contaminated by exogenous materials. Such contamination may consist of deposition or recrystallization of exogenous minerals within the normal spaces in the bone architecture. Deterioration of the organic collagen architecture of the bone provides a further context for mineral exchange, speeding the process of diagenetic exchange. Diagenesis and contamination are concerns for both trace element and stable isotope analyses. Since highly carbonated hydroxyapatite is quite soluble (Le Geros 1981), efforts to minimize both contamination and diagenesis have emphasized the dissolution of surface mineral with a buffered, dilute acetic acid (Crowley and Wheatley 2014).

Early research in bone chemistry attempted to examine exchange between bone and the burial context by searching for patterning between bone and adjacent soil, with variable success (Lambert et al. 1984). Screening methods to identify bones with higher levels than expected of nonbiological contaminants have been more useful. For instance, iron, aluminum, potassium, and rare earth elements are not found in appreciable levels in bone, and when found, they signal contamination from soil or the burial environment. High barium levels may indicate the crystallization of barite (barium sulfate) in bone lacunae, while microbial action may deposit magnesium oxides on bone in the burial context. Therefore, multi-element studies of bone mineral can identify elevated Sr or Ba levels that should be ascribed to diagenesis rather than diet (Price 1989). Examining the chemical composition of bone can be done via different analytical

instruments, including atomic absorption spectroscopy, particle induced X-ray emission (see ION BEAM ANALYSIS (PIXE/RBS) and PIXE AND MATERIAL ANALYSIS), mass spectrometry (see MASS SPECTROMETRY (MS)), X-ray fluorescence spectroscopy (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), inductively coupled plasma mass spectrometry (see ICP-MS AND MATERIAL ANALYSIS), and neutron activation analysis (see NEUTRON ACTIVATION ANALYSIS (NAA)). Stable isotope ratios are measured by mass spectrometry or thermal ionization mass spectrometry. Data collected following laser ablation can allow smaller sample sizes for some of these modalities.

SEE ALSO: Conservation of Bone, Horn, and Ivory; Diagenesis of Bone; Diet and Nitrogen Isotopes; Diet and Sulfur Isotopes; Diet and Trace Elements; ICP-MS and Material Analysis; INAA and Material Analysis; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Ion Beam Analysis (PIXE/RBS); Isotopes; Mass Spectrometry (MS); Mobility and Lead Isotopes; Neutron Activation Analysis (NAA); PIXE and Material Analysis; X-Ray Fluorescence Spectrometry (XRF)

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Imaging in Human Remains

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Background and development

Paleoradiology can be defined as the use of medical imaging techniques such as conventional X-ray imaging, X-ray computed tomography (CT), X-ray microtomography or computed microtomography (micro-CT) and magnetic resonance imaging (MRI) for the study of bioarchaeological materials.

In the first two decades after the discovery of X-rays by Wilhelm Conrad Roentgen (1845–1923) in November 1895, radiological studies were conducted by scientists from various backgrounds, including photographers, chemists, physicists, and physicians. Indeed, from its early beginnings, the discipline of paleoradiology arose in parallel with the development of radiology and medical imaging technology.

Since Roentgen had waived any patent protection of his discovery and published it in an “open source” manner, knowledge about his experimental setup swiftly spread around the world (Roentgen 1959). In March 1896, only a few months after Roentgen first published his discovery, the physicist Walter Koenig (1859–1936) published the first radiographic image of a bandaged ancient Egyptian child mummy from the Senckenberg Museum of Natural History, Germany (Koenig and Barth 1896). The plain anteroposterior X-ray image of this mummy’s knee region was the very first of its kind. It is of astonishing quality even by modern standards. The radiographic equipment of the time was mobile and was used on site, but required a long exposure time, of several minutes. In the following years, further researchers, primarily in Europe and in the United States, performed similar radiological investigations of ancient human remains (Boni, Ruhli, and Chhem 2004). The

most common countries of origin of mummies investigated at the beginning of the twentieth century were Egypt and Peru. For example, in 1904 the anatomist and anthropologist Sir Grafton Elliot Smith (1871–1937), assisted by Howard Carter (1874–1939), was able to determine the age at death of King Tutmosis IV through an X-ray examination of his mummy (Smith 1912). The term *paleoradiology*, however, was introduced much later, by Derek Notman and his colleagues in 1987, after an examination of the frozen bodies of three British sailors, members of the ill-fated 1846 Franklin expedition to the Northwest Passage in the Canadian arctic (Notman et al. 1987).

In current clinical practice the established imaging techniques (conventional X-ray, CT, and MRI) are widely used to diagnose diseases. Paleoradiological imaging is nowadays applied in a similar manner, in order to detect and describe pathologies and variations in normal anatomy. The purpose of the very early X-ray studies often was, on the contrary, simply to distinguish authentic mummies from replicas and to search for burial goods. Subsequently the identification of skeletal diseases or the evaluation of bone age became the focus of attention.

With the introduction of CT in the early 1970s, the application of paleoradiology expanded substantially; noninvasive analyses of body cavities were now possible. Godfrey Hounsfield (1919–2004) and Allan M. Cormack (1924–98) independently described this X-ray-based cross-sectional imaging technique, for which they were awarded the 1979 Nobel Prize in Physiology and Medicine. In 1976 Lewin and Harwood-Nash performed the first CT examination of mummified tissue from ancient Egypt. They imaged the desiccated brain of Nakht, the mummy of an adolescent male from the twenty-first dynasty, as well as the complete body of Djedmaatesankh, the mummy of an adult female from the twenty-second dynasty, both from the collection of the Royal Ontario Museum (Harwood-Nash 1979). In mummy research nowadays CT imaging is commonly used to non-invasively examine a range of parameters such as

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bone and soft tissue preservation, postmortem damages, mummification and embalming techniques, sex, pathologies, traumata, traces of medical interventions, age at death, possible causes of death, and even artificial cranial deformation.

Micro-CT was later developed to improve CT image resolution. It is mostly used in scientific applications rather than in clinical imaging, since only small samples—a few centimeters in diameter—can be scanned. Micro-CT can be used to study ancient teeth or to investigate mummified materials and fossils, since it provides an excellent depiction of anatomical details at submillimeter resolution.

In the late 1970s, a team led by John Mallard built the first full body MRI scanner at the University of Aberdeen; and in 1980 the first clinical MR images of a patient were acquired using this machine (Mallard et al. 1979). However, for over two decades, MRI has not been considered suitable for paleoradiological studies, since the MRI signal generally originates from free water in the imaged tissue, which is not present in desiccated ancient human remains. In an extreme attempt, even rehydration of desiccated ancient human tissue was tried, which obviously led to the loss of the specimen (Shin et al. 2010). Novel MRI techniques can now detect remaining bound tissue water in desiccated bioarcheological samples and permit nondestructive acquisition of high-quality MR images. Their common key element is the ability to compensate for the rapid MR signal decay in bound tissue water, for example by using ultrashort echo time sequences (UTE).

Indications and implications

The application of standard medical imaging techniques in bioarcheological investigations can serve many purposes and requires a distinctive methodology. Unfortunately the use of imaging technology is often limited by multiple factors, such as the availability and portability of the imaging equipment, financial costs, and challenges related to obtaining permission to move or transport ancient specimens for examination.

Thus conventional (digital) X-ray remains the primary modality for paleoradiological imaging. Portable digital imaging units can even be used for examinations at excavation sites or in museums. Most importantly, conventional X-ray also provides higher spatial resolution than CT or MRI (See Figure 1a and b). Despite of the wider availability of CT and MRI, or even of micro-CT, these modalities still serve mostly to clarify findings already seen on conventional X-ray images.

The focus of paleopathological studies is on the identification of pathologies and variations in normal anatomy, and the list of radiologically documented pathologies in ancient human remains essentially covers all major groups of pathologies known today.

An understanding of the characteristics of bioarcheological materials and postmortem changes is essential to establishing a careful differential diagnosis of paleoradiological findings. Dry-bone specimens or mummified remains show substantial variations in composition. In general they are dense, owing to the loss of water, and this makes it difficult to distinguish between different types of tissue. In addition, infiltrates from the surrounding soil may mimic sclerotic areas, while bone degradation due to acidic soil conditions can easily be mistaken for osteolytic processes. Substances employed during a mummification or embalming process or added later, during museum curation, will also alter a tissue's radiological appearance. Skeletal alterations typically associated with traumatic or rheumatologic diseases are the most frequent findings; but tumors have also been described in various studies. However, many skeletal lesions share common, nonspecific radiological characteristics, while pathognomonic patterns are rather rare and only apply to a few skeletal lesions such as fracture, nonossifying fibroma, and osteochondroma. The time of occurrence (peri- vs. postmortem) of a specific trauma is difficult to assess radiologically, unless signs of bone remodeling are present. Besides pathologies in hard tissues, disorders in soft tissues can also be identified. Mummies of different origins often have well identifiable cardiovascular structures where calcifications can frequently be found as evidence of atherosclerosis. X-ray images or CT scans also permit measurement of anatomical structures, which is taken in

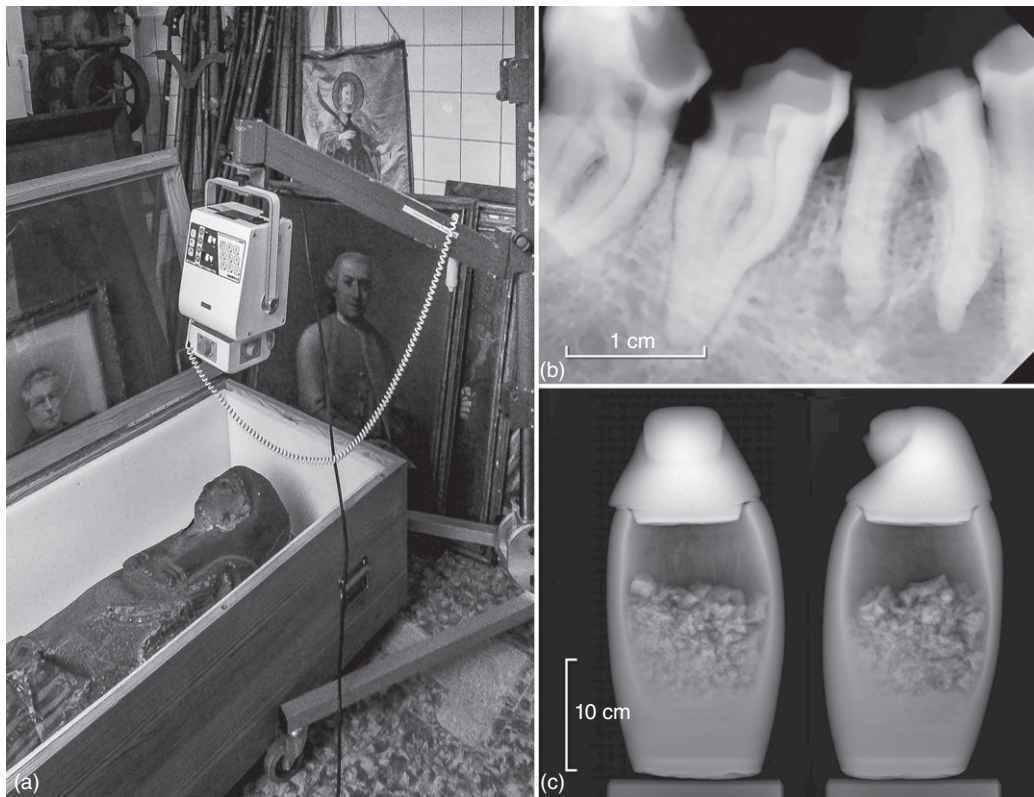


Figure 1 (a) Typical situation: radiographing an ancient Egyptian mummy with a mobile digital X-ray unit on site, at the Municipio di Brissago, TI, Switzerland. Source: Photograph by Patrick Eppenberger, Institute of Evolutionary Medicine, University of Zurich, Switzerland. (b) High resolution X-ray image of the posterior region of the mandible of an Egyptian mummy, radiographed on site at KV40, Valley of the Kings, Egypt, using a dental detector (image size: 27 x 36 mm; original resolution: 1440 x 1920 pixels). Source: With kind permission of the University of Basel, Kings' Valley Project and Roger Seiler, Institute of Evolutionary Medicine, University of Zurich, Switzerland. (c) Conventional X-ray images of a Canopic Jar consisting of limestone, ap (left) and lateral (right), with the Lid representing a hawk (Qebehsenuef), thus putatively to containing intestines. Source: With kind permission of the "Rijksmuseum van Oudheden," Leiden, the Netherlands.

order to determine the stature, the age at death, and the sex of an individual (e.g., of a wrapped mummy) for paleoanthropological studies.

Indeed, CT has even been used to identify skeletal remains embedded in a soil matrix, without destruction of the fragile specimens (Chhem, Brothwell, and SpringerLink 2008). Such specimens may also contain materials of high density and atomic number, such as funerary accessories, jewelry, tools, weapons, or body adornments. On the other hand, the bioarcheological material can itself be contained in a stone or ceramic vessel;

for example, mummified organs can be found in Egyptian Canopic jars (Figure 1c).

Concerns about the use of ionizing radiation when ancient human remains are imaged are legitimate, since such specimens are unique and irreplaceable. However, ionizing radiation from natural sources (like cosmic radiation and radon gas) has constantly affected any ancient specimen over time, thus in theory resulting in an integrated dose two, three, or even four magnitudes higher than the dose applied for an X-ray or CT examination.

Further techniques and future directions

Throughout its history, paleoradiology has benefitted from close interdisciplinary collaboration between radiologists, paleopathologists, and bioarcheologists, as well as other basic scientists. To achieve an improved differentiation of historical mummified tissue, various new methods based on CT, MRI, and even terahertz (THz) imaging have recently been applied in interdisciplinary research projects.

As mentioned, standard MR-imaging of dry tissue is generally limited by the low content of protons in the material. Newly developed, mostly UTE-based, MRI sequences for ancient remains are likely to provide images with significantly improved contrast and resolution, possibly surpassing X-ray-based imaging technologies in the future. MRI of other nuclei than hydrogen (^1H), such as sodium (^{23}Na) or carbon (^{13}C), is another promising technique, especially for the examination of Egyptian mummies, since Egyptian embalmers used natron, a mixture of sodium carbonate and sodium bicarbonate, for mummification.

A more recent development in CT scanning is known as dual-energy computed tomography (DECT). By using two different tube potentials, two CT datasets can be acquired with different X-ray spectra. The additionally obtained spectral information can then be exploited to identify elements of different atomic number. This can be particularly helpful in the analysis of mummified remains, as they often contain many types of materials (bone, cartilage, soft tissues, hair, embalming materials, textiles, wood, or even metal parts).

THz imaging is of particular interest, since it is a noninvasive and nonionizing diagnostic modality. While clinical imaging applications in the THz frequency range (100 GHz–5 THz) are quite limited by the strong absorbing properties of water, the low water content of most bioarcheological materials facilitates THz investigations. However, due to the greater wavelengths, THz radiation will always provide lower spatial resolution than X-ray based imaging or MRI. Nevertheless it has potential, for example in the recognition of hidden objects in historic samples, or in the

identification of specific spectral signatures from chemical substances used for embalming.

Such techniques, novel to the field of paleoradiology, are now increasingly used to expand diagnostic capabilities in unique human tissue samples. But advances are also being made in the way imaging data can be further processed. 3D printing techniques allow multiple copies and hands-on access to specimens without damaging or even touching the original.

Paleoradiology will inherently remain an experimental discipline, where each method offers its benefits and limitations. The decision about the best approach will thus continue to benefit from close interdisciplinary collaboration between scientists from different disciplines.

SEE ALSO: Archaeological Sciences; Bones and Ivory; Computational Photography

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Infant Feeding

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The study of infant and young child feeding in past populations is an active area of research because early diet, nutrition, and health are key determinants of childhood survival and adult health. The duration of breastfeeding can ultimately influence the demographic profile of a population because breastfeeding can suppress ovulation and increase interbirth intervals. The term “infant” usually refers to individuals under one year of age, so when discussing infant and young child feeding, this covers the period from birth through the completion of weaning and the shift to a post-weaning diet. There is a general human pattern of exclusive breastfeeding to six months of age, followed by the weaning process that is characterized by an extended period of transitional feeding with complementary foods (Sellen 2007). Exclusive breastfeeding provides energy and nutrients to the growing infant and also protects against infections and disease through passive immunity provided by maternal breast milk. The duration of breastfeeding is critical for the survival of the infant; too little breastfeeding can lead to high rates of infant morbidity and mortality, whereas extended exclusive breastfeeding beyond six months of age may not provide the necessary energy and nutrient requirements for normal growth and development. This is known as the “weanling’s dilemma,” that is, the balance between the nutritional and energy requirements of growing infants and their immunological development. Despite a general life-history pattern of infant feeding in human populations, there is considerable variability in the timing and duration of breastfeeding related to both individual choice and broader cultural attitudes and norms. Of interest to researchers studying archaeological populations are the social, political, and economic factors that

may have impacted breastfeeding and weaning practices.

Weaning is a process characterized by the gradual removal of breast milk and the introduction of complementary foods, and it ends with the complete cessation of breastfeeding. Prior to the use of biochemical techniques to investigate patterns of infant and young child feeding in past populations, weaning was often inferred from osteological indicators of stress (e.g., enamel hypoplasias, Harris lines, cribra orbitalia, and porotic hyperostosis), because these indicators were thought to be related to weaning stress. This is because during the weaning process, infants come into contact with pathogens present in complementary foods and water, and have greater interactions with their environment, putting them at greater risk for illness and death. There are, however, problems with using these osteological indicators to infer infant and young child feeding, not the least of which is that they can be caused by a variety of stressors including diet, disease, and trauma.

Elemental studies of breastfeeding and weaning in archaeological contexts have analyzed strontium (Sr) to calcium (Ca) ratios in bone, because Sr/Ca ratios are lower in infants who exclusively breastfeed (Sellen and Smith 1984). There is also potential in the study of barium (Ba) to Ca ratios in relation to breastfeeding and weaning, as Ba/Ca ratios are higher in breastfeeding infants, but this has not been widely used in bioarchaeological studies. Concerns over the relationship of trace element data to diet and diagenetic effects on trace element values in buried bone have limited the use of Sr/Ca ratios to study weaning patterns, although the use of tooth enamel is promising, as it is more resistant to diagenesis.

The stable isotopes of nitrogen ($\delta^{15}\text{N}$) and carbon ($\delta^{13}\text{C}$) in bone collagen are most often used in biochemical studies of breastfeeding and weaning, although oxygen ($\delta^{18}\text{O}$) isotopes have also been employed. Nitrogen isotopes are regularly used in weaning studies based on the “trophic-level effect,” in which the $\delta^{15}\text{N}$ tissue

values of consumers are higher than those of the foods consumed (by 2–4‰) (per mil), although the magnitude of this difference varies between species. Studies of modern mother–infant pairs demonstrated that the $\delta^{15}\text{N}$ values in the finger-nails and hair of exclusively breastfeeding infants were higher than those of their mothers (by 2–3‰) and there was also a similar, but smaller (1‰), trophic-level shift in $\delta^{13}\text{C}$ values (Fogel, Tuross, and Owsley 1989; Fuller et al. 2006). Once the weaning process starts and breast milk is removed from the diet, $\delta^{15}\text{N}$ values decrease to reflect the removal of breast milk. A sharp decrease in $\delta^{15}\text{N}$ between age groups is interpreted as the rapid removal of breast milk from the diet, whereas a gradual decrease is interpreted as a more drawn-out weaning process. There are, however, a number of underlying assumptions implicit in the use of $\delta^{15}\text{N}$ data in weaning studies, such as: the adult female $\delta^{15}\text{N}$ mean is equal to that of the mothers who provided milk, there is little variability in adult female diet, diet-to-tissue offsets in $\delta^{15}\text{N}$ values are the same in both adults and infants, and the weaning trajectories of young children are identical (Reynard and Tuross 2015). An additional complicating issue is that $\delta^{15}\text{N}$ values in infant bones can be influenced by factors such as maternal diet, stress during fetal development, stress associated with malnutrition or disease in the infant, and the physiological demands of growth, all of which can variably impact $\delta^{15}\text{N}$ values.

Carbon isotope ratios are not typically used on their own to track breastfeeding and weaning due to the smaller trophic-level effect, but $\delta^{13}\text{C}$ values are used in concert with $\delta^{15}\text{N}$ data to detect the introduction of complementary foods. The analysis of $\delta^{13}\text{C}$ data can be used to infer the use of C^4 -based weaning foods, such as millet or maize, or the early introduction of marine foods in the weanling diet, all of which result in higher $\delta^{13}\text{C}$ values. Oxygen isotopes ($\delta^{18}\text{O}$) are used to investigate geographic origins and mobility in past human populations (see MOBILITY AND OXYGEN ISOTOPES), because the oxygen in local precipitation largely determines $\delta^{18}\text{O}$ values in human tissues, and varies in relation to latitude, elevation, temperature, humidity, and distance from water. The $\delta^{18}\text{O}$ signals of exclusively breastfeeding infants are higher than adult female values (by $\sim 2\text{‰}$), because human breast

milk is produced from available body water that is enriched in ^{18}O over the water consumed by the mother. Oxygen isotope values are usually obtained from tooth enamel, so the isotopic analysis of permanent teeth formed at different periods during infancy and childhood can be analyzed, and lower $\delta^{18}\text{O}$ values in progressively later forming teeth are used to infer that weaning occurred (Wright and Schwarcz 1998). $\delta^{18}\text{O}$ values in bone can also be used to investigate breastfeeding and weaning patterns, but it is necessary to consider variability in bulk bone $\delta^{18}\text{O}$ values associated with seasonal variation in climate, mobility, and seasons of birth and death.

Stable isotope data are usually obtained from bone collagen samples, which reflect the protein composition of the diet, and information on total diet is derived from bone apatite (the inorganic portion of bone). One issue with using bone is that it has a relatively slower turnover time than other body tissues like hair and nails, so there is a lag time between changes in diet and a record of this shift in bone. This lag time is estimated to take weeks to a few months, depending on the rate of bone formation and turnover, which is not well understood. In an effort to contend with the issue of lag time in bones and to develop a more precise estimate of the timing and duration of breastfeeding and weaning, Tsutaya and Yoneda (2013) employ mathematical modeling to estimate the initiation and duration of the weaning process.

A confounding issue in studying infant and young child feeding in past human populations is that the data are derived from mortality samples, that is, from those individuals who did not survive infancy and childhood. In order to reconstruct breastfeeding and weaning patterns, the sample is necessarily cross-sectional (i.e., bones are sampled from deceased individuals in each age category). Thus, we do not know if these nonsurvivors were breastfed and weaned in the same manner as survivors. In order to contend with some of the issues associated with using bone of nonsurvivors for isotopic analyses, sequential samples of tooth enamel and dentine are now a focus of study. These tissues form during infancy through adolescence and remain relatively unchanged throughout life, so the sequential analysis of permanent teeth means that isotope data about breastfeeding

and weaning are obtained from individuals who survived childhood, minimizing the issue of mortality bias in stable isotope studies. Sequential samples from teeth can track intra-individual (i.e., longitudinal) dietary variation and result in more precise estimates of the timing of breastfeeding and weaning, because the stages of tooth development are well known. Advances in microsampling of teeth and developments in mass spectrometry mean that smaller sample sizes can be used for isotopic analysis and greater temporal resolution can be obtained (Henderson, Lee-Thorp, and Loe 2014). One problem is that enamel and dentine do not grow in horizontal layers, so serial sections taken from teeth (usually done horizontally) may represent overlapping periods.

It is important to recognize the underlying assumptions and limits of stable isotope analyses, particularly with respect to data derived from the bones of nonsurvivors. New methods of isotope analysis are enhancing our understanding of infant and young child diet in the past, and offer greater precision in the estimation of when this important first dietary transition occurred in past populations.

SEE ALSO: Bioarchaeology; Diet and Carbon Isotopes; Diet and Nitrogen Isotopes; Diet and Sulfur Isotopes; Diet and Trace Elements; Isotopes; Osteology

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Infectious Disease

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Much of the study of infectious or contagious diseases within the archaeological record has occurred within the fields of paleopathology (see PALEOPATHOLOGY), the study of ancient disease, and paleoepidemiology, the study of population-level disease dynamics within past populations. However, an increasing body of work on the issue has recently emerged from biomolecular research: ancient DNA studies (aDNA) (see GENETICS: ANCIENT), archaeogenetics, the application of population genetics to the study of past populations, and ancient pathogen genomics, the study of ancient pathogen genomes (see GENOMICS: ANCIENT), as well as related fields. Motivations for these inquiries have shifted throughout time. Infectious disease, particularly treponemal disease (i.e., syphilis, yaws, bejel), was a major focus of paleopathological inquiry in the late nineteenth to early twentieth century, soon after the field's late-eighteenth-century emergence. These works took the form of case studies and were focused on the individual case studies of single disease episodes and documentation of the presence of different types of infectious diseases across cultural and temporal contexts. With the inception of paleoepidemiological research in the 1960s and 1970s, analyses of infectious disease in the archaeological record have increasingly shifted towards population-level analyses of the ecology and evolution of infectious diseases and of interactions between pathogens and their human hosts. Augmented and enabled by innovations in biomolecular research since the 1990s and early 2000s, contemporary research on infectious disease within the archaeological record is largely oriented towards characterizing coevolutionary relationships between human hosts and their pathogens and interactions between humans, pathogens, and their environments. Within this, analyses frequently focus

on how these dynamics have impacted human evolution, especially susceptibility to disease, and pathogenic evolutionary responses to biological, economic, social, and technological changes within human societies over time.

Issues impacting the study of infectious disease in the archaeological record

Several material issues impact the study of infectious disease in the archaeological record. Some of these have been largely resolved recently, but others are characteristic of archaeological human skeletal material, or are unique to the study of disease in the past and therefore persist. Material limitations that are fundamental to archaeological research include small sample sizes and the frequently poor preservation and incompleteness of archaeological material, including skeletal material. More unique to the study of disease is the issue that few diseases, including infectious diseases, affect the skeleton, and those that do are typically chronic (versus acute) in course. This limits the archaeological visibility of many diseases. Up until recent innovations in biomolecular research, this effectively limited inquiry to a relatively short list of chronic infectious conditions. These included some macroparasitic organisms, such as intestinal worms, as well as microparasitic diseases such as tuberculosis, leprosy, and treponemal disease. Another issue is that the skeleton can only physiologically respond to insult in a limited way, which means that different diseases can produce highly similar manifestations. Only a few diseases produce highly specific, diagnostic lesions. This means that many diseases, including infectious diseases, cannot be macroscopically or grossly identified in skeletal material with a great degree of accuracy. Whether infected individuals manifest skeletal lesions is further moderated by host resistance factors, namely age, sex, health status, and immunological competence. Viewed within a biocultural model, these factors are both produced and influenced by environmental constraints and conditions.

Communities can strategically buffer themselves against their environments through technologies, social organizations, and ideologies. This can reduce individual-level vulnerability to infection, risk of additional infection (co-infection), and associated morbidity and mortality. However, in socially stratified societies, these strategies can buffer privileged individuals while exacerbating stressors and their effects for the disadvantaged, increasing their vulnerability to infectious disease. Some cultural practices can also act as stressors, such as the use of irrigation agriculture and the associated rise of water-based infectious diseases, such as schistosomiasis, an acute and chronic disease caused by parasitic worms.

Several methodological and theoretical issues also impact the study of infectious disease within the archaeological record. One methodological issue is that the popularity of case studies prior to the 1960s and 1970s greatly limited population-level analyses of the evolution, coevolution, and ecology of diseases within past human populations. Another is that evidence-based, standardized diagnostic criteria that incorporate concepts from differential diagnosis in clinical medicine and disease screening within epidemiology exist for only a small number of infectious conditions that affect the skeleton. These include treponemal disease, malaria, and leprosy (see DIFFERENTIAL DIAGNOSIS). Infectious diseases that do not produce clear diagnostic skeletal changes cannot be diagnosed with nearly the same accuracy. Many researchers also do not use the same set of diagnostic criteria, which reduces the comparability of various studies and their results (Zuckerman, Harper, and Armelagos 2016).

The osteological paradox

Several theoretical issues are fundamental to archaeological research, such as the time frame(s) represented by archaeological assemblages (time averaging), selection biases that arrive from mortuary and related practices (see MORTUARY ANALYSIS), and issues of the representativeness of a given archaeological sample. Two additional factors, which are key components of the osteological paradox, further impact the issue of sample representativeness in research reconstructing past health and disease (Wood et al.

1992). These are hidden heterogeneity in frailty and selective mortality (see PALEODEMOGRAPHY AND HAZARDS ANALYSIS). Hidden heterogeneity in frailty comprises individual-level variation in host resistance factors and consequently susceptibility to different diseases, as well as individual experiences of stress and risks of death. Selective mortality, which acts upon heterogeneity in frailty, means that skeletal samples composed of individuals with high age-specific frailty are therefore not representative of the less frail members of the original living population (Wood et al. 1992). Together, these issues directly impact population-level research, preventing direct inferences about disease, as well as health, in past populations from archaeological skeletal samples. With regard to infectious disease specifically, heterogeneity in frailty and selective mortality have been extensively explored for some diseases and disease events, but not yet estimated for others. Much of this research has focused on plague, caused by *Yersinia pestis*, specifically the fourteenth-century epidemic known as the Black Death. The short chronologies characteristic of mass graves created by epidemics have allowed researchers to reduce the role of confounding variables, such as temporal changes in diet and disease ecology, in investigating whether mortality from the plague was indiscriminate with regards to the age and previous health experiences of victims (see DeWitte and Stojanowski 2015). While archaeological skeletal samples with short chronologies, such as mass graves, are relatively rare, they were often produced by epidemics of acute disease in the past. These samples can therefore provide valuable opportunities to explore issues of selectivity and heterogeneity, and therefore increase the accuracy of estimating the impacts and dynamics of infectious disease in past populations, particularly for acute diseases that can otherwise be difficult to study archaeologically.

Biomolecular advances in the study of infectious disease in the archaeological record

Methodological advances, particularly in biomolecular research, have also greatly expanded

scholarly understanding of infectious diseases in past populations. Importantly, after the pioneering studies of pathogen aDNA in the 1990s and early 2000s, the application of biomolecular methods has matured and become highly sophisticated, resulting in theory-building, the examination of existing research questions, and the generation of new ones, rather than method-driven research. Biomolecular techniques have been applied to a growing range of infectious diseases, enabling identification and analysis of infectious diseases that do not affect the skeleton, or do not always do so in a distinctive or specific way. These include smallpox, influenza viruses, typhoid fever, schistosomiasis, typhus, cholera, and the plague. Used with more traditional macroscopic methods, biomolecular techniques have also increased the accuracy of diagnosis and expanded the areas for studying diseases that do affect the skeleton in more distinctive and specific ways, such as tuberculosis, leprosy, malaria, and brucellosis.

The evolution of pathogens and coevolution of pathogens and their human hosts

The detection of some infectious diseases, such as treponemal disease, through biomolecular methods remains largely elusive due to methodological and material issues, such as the sometimes poor preservation of aDNA in skeletal material. However, diverse sampling strategies and enrichment techniques may increase the range of infectious conditions that can be analyzed through pathogen genomics. Among other insights, biomolecular research on pathogens recovered from archaeological remains, particularly aDNA, contributes to scholarly understanding of the evolution of infectious disease by providing granular, time-stamped data for reconstructing phylogenies. These data in turn allow scientists to test hypotheses about the histories of human–pathogen coevolution and resulting adaptations (see *DNA: NEXT GENERATION SEQUENCING*). Much of this research has focused on comprehending the coevolutionary dynamics and shifts in patterns of human susceptibility to infectious disease that have occurred throughout

major economic and societal developments in human history. These investigations frequently integrate biomolecular data, particularly from ancient pathogen genomics, with direct skeletal data on infectious disease, as well as archaeological, historical and/or ethnographic data. These diverse lines of evidence allow scientists to reconstruct how changes in subsistence, economic development, and social practices and processes altered patterns of pathogen transmission, mortality and morbidity within human populations, and the survival and reproduction of pathogens (Harkins and Stone 2015).

The major economic and social developments being investigated include agricultural intensification and industrialization. Paleolithic foraging societies were likely characterized by a relatively low burden of infectious diseases. In the Neolithic, agricultural societies shifted to an epidemiologic regime with a relatively high burden of infectious diseases, particularly epidemic infections. The burden was associated with increased sedentism and population density, reduced environmental quality, and increased contact with domesticated animals. The latter yielded a rise in zoonotic infections (diseases transmitted from animals to humans), such as smallpox, many of which caused high mortality in human populations. This shift in epidemiologic regimes is known as the first epidemiologic transition. Comparisons between the epidemiologic baseline of the Paleolithic and the subsequent epidemiologic regime provide a useful platform for developing hypotheses about relationships between human–pathogen interactions and social and economic change (Armstrong, Brown, and Turner 2005). Importantly, analysis of past transmission events between animals and humans can also inform the reconstruction and modeling of human–pathogen interactions in present and future contexts, with direct implications for public health measures (Harkins and Stone 2015). The high burden of epidemic infectious disease was exacerbated by increasing urbanization and industrialization in developed nations. However, public health measures, improved nutrition, and medical advances led to declines in the burden in developed nations in the late nineteenth and early twentieth centuries, producing increasing longevity and an increased burden of chronic and degenerative disease. This shift is known as

the second epidemiologic transition (Armélagos et al. 2005). Analyses of this trend, which do not yet substantially incorporate biomolecular methods but rely primarily on historical material augmented by skeletal and archaeological data, enable comprehension of the complex dynamics that exist between urban environments, particularly relative to sanitation and public health measures, medical advances and practice, pathogens, and their human hosts.

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Life Table Analysis

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Population dynamics and demographic patterns are subjects of analysis that transcend the social, behavioral, and biological sciences. For archaeologists, research questions often revolve around population growth, stability or decline, gene flow and immigration, and the demographic and epidemiological transitions experienced by populations from the late Pleistocene through the Holocene. In this context, *abridged life tables* provide one means of assessing and comparing basic demographic patterns in past societies and of detecting bias and underrepresentation of age classes and sexes in excavated samples. Chamberlain (2006) provides useful instructions on how to develop life tables from skeletal data, including corrections for varying growth rates that are based on model life tables. The construction of a life table for an archaeological sample is typically predicated on the analysis of human skeletal remains from a site and, at minimum, on estimates of age at death for all well-preserved skeletons and of sex for the mature, reproductive-age individuals. Analysts are typically observing skeletal indicators of development, growth, or breakdown at the macroscopic level and translating those observations into an estimate of chronological age for each skeleton. The individual age-at-death estimates are then tabulated into pertinent age categories at the discretion of the analyst, who can now begin the development of an abridged life table for an archaeological sample.

Life tables were originally developed by demographers and actuary scientists and are best exemplified in policies such as social security and health insurance, where life expectancy and other factors (e.g., preexisting conditions) play critical roles in determining current and future costs and reserves. From cohorts of the living, basic life tables include the proportion

of living (c_x) and deaths (d_x), survivorship (l_x), the age-specific probability of death (q_x), and life expectancy (e_x) within researcher-specified age ranges (e.g., 0–1, 1–2, 2–5 yrs.). Provided large and representative skeletal samples, significant inferences and comparisons can be achieved in paleodemography. Importantly, the use of the term “abridged” in life tables reconstructed for past populations reflects the fact that all individuals examined are observed at the time of death, which is different from the situation reflected in the census-driven or cross-sectional life tables developed by demographers. As discussed below, this difference complicates the analysis and interpretation of life tables in archaeology, but does not suggest that wholesale abandonment is required. However, it is important to recognize what abridged life tables can and cannot effectively measure about past population dynamics.

Like other specializations in archaeology, the codification of paleodemography and the use of abridged life tables followed the processual turn in the discipline that occurred in the 1960s and 1970s. Acsádi and Nemeskéri (1970) were among the first to implement life tables in examining demographic patterns in a series of Hungarian skeletal samples, and they argued that life expectancy increased with the Neolithic revolution in central Europe. This work was soon followed by Weiss (1973), who published model life tables that assumed population stationarity (i.e., zero growth) and reflected the hypothetical gamut of age-specific mortality and fertility rates anticipated among traditional anthropological populations. The importance of Weiss’s simulations and of more recent research on demographic patterns in traditional populations cannot be overstated for scholars who endeavor to understand population dynamics and compare death assemblages from archaeological sites to known case studies of foragers, pastoralists, and farmers. Meanwhile, in the United States, life tables were used by a host of researchers during the 1970s. This included the highly influential studies of the diachronic skeletal samples from Dickson Mounds in Illinois (Lallo, Rose, and Armelagos 1980), where

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agriculture was interpreted as having a negative impact on life expectancy and health among New World peoples who inhabited the region. Among the various life table measures calculated, life expectancy at birth (e_0), sometimes referred to as the mean age at death, was the primary focus of interpretation.

During the 1980s, life tables and paleodemography faced legitimate criticisms on several fronts; this resulted in a proactive debate that continues to this day. Methodologically, researchers astutely observed that the adult age estimation techniques used by practitioners were deficient and resulted in mortality profiles and life tables that resembled the age structure of the reference collection on which the skeletal aging technique(s) was developed. The result was a compression of the human lifespan into seven decades or fewer, large clusters of skeletons being estimated to have died between the ages of 30 and 50 and very few to have experienced senescence and old age (i.e., 65+ yrs.). Despite the fact that adult mortality rates varied in living populations, most abridged life tables yielded homogeneity, with minor differences in survivorship and life expectancy among adults in the associated skeletal samples. These outcomes suggested that old age was rare to nonexistent in the past, regardless of subsistence practices, population densities, disease ecology, and other factors of interest. Adult age estimation techniques continue to be refined and developed by practitioners in the archaeological and forensic sciences and there is a strong emphasis on establishing more accurate and precise estimates for the elderly. Progress on this front is exemplified in a volume edited by Hoppa and Vaupel (2002), where new age estimation and paleodemographic techniques are presented.

Concurrently, a second major criticism was leveled against abridged life tables as an appropriate means to assess differences in mortality within and between skeletal samples. Death assemblages are produced over varying lengths of time and catchment areas, not to mention sociocultural factors that dictate where specific individuals are buried and whether they are ultimately exhumed by archaeologists. In the context of cemeteries used for generations, fertility has a more significant impact on the age-at-death distribution (i.e., d_x) depicted in abridged life tables than mortality. Therefore, in the high-fertility

populations that likely characterized most of the Holocene until recently, life expectancy at birth, as presented in life tables produced in paleodemographic studies, is inversely correlated with population growth. The proportion of juveniles in death assemblages becomes a proxy measure of population growth, as recently illustrated by Bocquet-Appel (2011) for the Neolithic demographic transition.

Moving forward with life tables, the challenges are not insurmountable, as old skeletal data can be recalibrated and most age-at-death distributions have, at minimum, a heuristic value for researchers who attempt to identify systemic biases such as the underenumeration of infants or of the elderly. Given the quality of the data, hazard models provide a viable alternative to the tabulation procedures commonly used in the construction of abridged life tables. Contrary to life tables that require the estimation of numerous parameters, hazard models effectively capture the variability in mortality across of human lifespan, with a handful of parameters specific to the course of juvenile and adult mortality, while often accounting for the uncertainty associated with the original age estimation techniques. Furthermore, the estimated parameters of a hazard model can be used to calculate important vital statistics, such as age- and sex-specific life expectancies, survivorship, and the force of mortality. These estimates of past human population dynamics are of interest to a host of research areas beyond archaeology and have the potential to facilitate future interdisciplinary collaborations.

SEE ALSO: Bioarchaeology; Biological Distance; Differential Diagnosis; Estimating Adult Age at Death: Cranial Suture Closure; Estimating Adult Age: Auricular Surface Morphology; Estimating Adult Age: Pubic Morphology; Estimating Adult Age: Transition Analysis; Estimating Skeletal Sex: Cranial and Pelvic Morphology; Estimating Skeletal Sex: Metrics; Estimating Subadult Age: Dental Development and Eruption; Estimating Subadult Age: Diaphyseal Length; Estimating Subadult Age: Epiphyseal Union; Human Growth and Development; Human Populations; Human Skeletal Data Quantification; Infectious Disease; Mobility and Lead Isotopes; Mobility and Oxygen Isotopes; Mobility and Strontium

Isotopes; Mortuary Analysis; Osteology;
Paleodemography; Paleodemography and
Hazards Analysis; Paleopathology; Radiocarbon
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Malnutrition

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The study of paleonutrition and paleopathology (see PALEOPATHOLOGY) provides an important time depth to the field of nutritional anthropology. Archaeological and skeletal evidence (see OSTEOLOGY) related to past diets, health, and nutrition brings home the holistic nature of a discipline that crosscuts the entire field of anthropology. The focus of this brief discussion centers on how the study of malnutrition and human skeletal biology came to the crossroads of human health, what has been done, and what could be accomplished. Malnutrition is a lack of a key component in one's diet. Traditionally, anthropologists have focused on several key components associated with bone health; these include iron and protein, and vitamins D, C, and B₃.

The study of ancient food-cultures that lack iron (see DIET AND TRACE ELEMENTS) as a key mineral associated with a healthy diet is seen in many publications concerning skeletal biology and malnutrition (Angel 1966; Stuart-Macadam 1992). In summary, the skeletal lesions often connected to chronic anemia (see ANEMIA) caused by an iron-diminished diet are porotic hyperostosis, cribra orbitalis, and long bone periostitis. This research has concerned itself with how anthropologists record, score, and define these lesions. Typically, small pits found on the skull are considered to be healed/inactive lesions, while hair-on-end lesions are active lesions. The debate continues as to what iron deficiency in ancient peoples truly reflects, that is, whether active lesions or healed lesions tell us a similar story. Other considerations still under discussion are how much of what is seen is specific to diet or parasitic causes or the result of epigenetic origins (see DIFFERENTIAL DIAGNOSIS).

Protein malnutrition is a key metabolic disorder (see METABOLIC DISEASE) for many past and present human communities (Goodman et al. 1988; Larsen et al. 2002). Protein-calorie malnutrition (PCM) refers to an inadequate calorie and/or protein intake. It is a dietary issue associated with a lack of meat, fish (see ZOOARCHAEOLOGY AND HUMAN DIET RECONSTRUCTION), and plant foods (high protein content). In living people, protein deficiency is often linked to low calorie intake; as such, the condition is referred to as marasmus, while kwashiorkor refers to a lack of protein with an adequate intake of calories. Skeletal lesions associated with PCM are also linked with general infectious agents (see INFECTIOUS DISEASE). Low protein intake often leads to an impaired immune system (Brinkey and Ives 2008). With an impaired immune system, individuals are subjected to a variety of infectious agents (bacterial and viral) that will affect bone biology. Skeletal lesions often associated with this interactive process include osteomyelitis and periostitis, the pitting and thickening of bone tissue.

A lack of vitamins may also influence health changes in bone. Vitamin C and its relationship to scurvy is well studied (Ortner and Eriksen 1997). Pitting on the sphenoid bone is considered one of the key skeletal lesions indicating a chronic lack of vitamin C. Ortner and others showed that vitamin C had been an overlooked dietary problem in subadult archaeological burials. Mays (2008) also provides an important summary specific to scurvy and vitamin C deficiency research. He notes, after prolonged and chronic episodes of scurvy in adults, that teeth are often lost and alveolar bone changes may occur. Unlike adults, children tend to show greater skeletal changes as a result of scurvy (Mays 2008). Ortner and Eriksen (1997) refer to this as infantile scurvy. They suggest that the cranial vault, eye orbits, the greater wing of the sphenoid, the maxilla, and the hard palate will show signs of pitting. Hence, when observed by anthropologists, the combination of these lesions is linked to scurvy in child burials.

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Vitamin D deficiency affects bone and is associated with a diet lacking in foods that provide vitamin D (for example, eggs, milk, fish) and a lack of UV-light exposure. Ortner and Putschar (1981) provide an important early reference for this metabolic disorder. The authors refer to vitamin D deficiency (rickets) as a disease found in children, characterized as a lack of mineralized cartilage and bone. As a dietary disorder, it ranks as one of the top three micronutrient deficiency issues studied by paleopathologists (Brinkley and Ives 2008). This form of malnutrition has been linked to agricultural practices and the expansion of human communities in the northern climates of Europe. Today, we see this condition in communities with inadequate diets and little sunlight exposure. For example, among the impoverished of New York City or the poverty-stricken ethnic groups of India that practice *purdah*. *Purdah* is when married women are kept in isolation. When demineralization of bone under these conditions occurs in adults it is called osteomalacia. Along with studies that focus on current communities, there have been numerous key studies of rickets among historic communities, such as from the burials excavated from the St. Martin's cemetery and from the Spitalfield church cemetery (Brinkley and Ives 2008). Both studies link environment, cultural practices, and diet to the increase in rickets among these people.

Using a biocultural approach towards understanding human diet and health, Paine and Brenton (2006) have argued that innovative interpretations about the diet, health, and paleomalnutrition of New World horticulturalists should emerge from hypotheses concerning skeletal manifestations and associated lack of iron, vitamin C, and niacin; the latter is associated with a chronic dietary condition known as pellagra. Paine and Brenton (2006) re-examine the skeletal signatures (cranial pitting, periostitis of long bones, and cortical bone loss) traditionally linked to maize intensification, and they point out that there is little critical discussion concerning the potential effect of pellagra on ancient Native American peoples. A passing mention of the "possibility" of pellagra in ancient skeletal populations has been noted by Larsen et al. (2002, 411). To further explore this overlooked issue, Paine and Brenton

(2006) focused on the inner-workings of rib micro-anatomy. The authors found that the rib shows signs of dietary deficiencies both in cortical bone and micro-anatomy relative to age-at-death. These results show the promise of how rib micro-anatomy can highlight how bone responds to chronic and seasonal bouts of nutrient starvation. It appears that vitamin deficiencies lead to less cortical bone in ribs and a fewer number of key micro-anatomical features.

A key concern of researchers studying malnutrition from the bioarchaeological record is the long-running debate about the osteological paradox. This debate centers on two issues: Do bioarchaeologists have adequate demographics to assess skeletal health from burials of unknown individuals, and do the presence or absence of skeletal lesions provide accurate insight into human health of past peoples? Goodman et al. (1988) have stated that skeletal lesions reflect stress indicators and can be used to measure the quality of health of ancient populations. This claim, echoed by many other researchers, was brought to a critical evaluation by Wood et al. (1992). Wood et al. raised the question as to whether burials with skeletal lesions accurately reflect the health status of past populations specifically and whether skeletons with lesions represent extremely ill individuals or those who are considered survivors. Are survivors healthy or are they just getting by? If the individual dies without exhibiting skeletal lesions, does this mean that this death represents an acute illness or simply one caused by agents that do not affect the skeleton? Since 1992, these questions continued to be difficult to answer. At present, it is reasonable to suggest that many paleonutritionists work under the assumption that individuals who exhibit skeletal lesions have suffered from chronic stressors (sometimes from chronic dietary-related stress episodes), while individuals who die young with few or no skeletal lesions die from acute ailments (Goodman and Martin 2002). This is a critical point to base observations from while attempting to interpret dietary-related skeletal lesions seen among ancient burials. Most of the skeletal lesions specific to dietary deficiencies will occur only if the deficiency becomes chronic. Many of these episodes occur seasonally and therefore may have been less chronic and were

survivable. Hence, a broad range of lesion variability may often be seen as individuals undergo chronic stress episodes followed by periods of recovery.

Importantly, the study of paleonutrition should be based on a synergistic relationship between dietary deficiencies and infectious agents. A lack of specific nutrients, minerals, and vitamins diminishes one's ability to fend off infectious agents. As a result, many of the skeletal lesions observed are often the result of both nutrient deficiency and the insult by infectious agents. Only the archaeological/environmental context can help to sort out the multilayered causes that produce skeletal defects. Hence, biocultural/cultural ecology approaches to interpreting the health status of past peoples are invaluable.

The next generation of paleonutritionists should continue to challenge the dogma of the discipline. One means for doing so would be to focus research on collections of skeletal material with known demographics. A growing but yet underused resource for such studies is the skeletal material housed at several human body farms organized by universities found in Tennessee, Texas, Colorado, and North Carolina. Although these academic research facilities are primarily used to conduct forensic/decomposition studies, there is no reason why this skeletal material could not be used for the assessment of bony lesions associated with health-/dietary-related research.

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Metabolic Disease

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Metabolic disease, or metabolic bone disease, represents a suite of conditions that cause an imbalance in normal bone remodeling processes. These conditions are of increasing interest to bioarchaeology (see BIOARCHAEOLOGY) as they lie at the intersection of human culture and health. By definition, metabolic diseases have nutritional, cultural, social, or genetic (see GENETICS: ANCIENT) causes rather than infectious ones. Yet some metabolic diseases can affect susceptibility to certain infectious diseases (see INFECTIOUS DISEASE), and others may arise as sequelae (i.e., consequential secondary conditions) spawned by a chronic infectious disease. Metabolic diseases can affect the whole body, as is the case with the general bone density reduction of osteoporosis, or may be limited to only a few focal areas, as with Paget's disease of bone. Bioarchaeologists use osteological (see OSTEOLOGY) evidence of metabolic disease found on human remains to infer genetic and cultural similarities, as well as social and sex-based differences, within past human populations.

Metabolic diseases are caused primarily by a deficiency or surplus of a particular mineral or hormone required in the formation or resorption of bone tissue. During bone modeling and remodeling, specialized osteoclast cells are signaled by cytokines, growth factors, and hormones to resorb bone. This is followed by the signaling of specialized osteoblast cells which deposit new bone matrix called osteoid. Osteoid is composed of the organic component of bone, including mostly collagen fibers, and the nonorganic hydroxyapatite, which subsequently mineralizes the matrix.

The main minerals implicated in bone homeostasis are calcium, phosphate, and magnesium, which all play a role in bone mineralization as the principal components of hydroxyapatite

($\text{Ca}_5(\text{PO}_4)_3(\text{OH})$). Other necessary minerals less frequently implicated in problems of bone homeostasis include fluoride, sodium, potassium, strontium, and citrate. Often deficiencies in any of these minerals stem from dietary and environmental factors. The main hormones required for normal bone maintenance are vitamin D, estrogen, parathyroid hormone, and to a lesser extent calcitonin, thyroid hormone, and vitamin A. Deficiencies in many of these hormones result from normal age-related decreases in hormonal production, but can also result from environmental and dietary factors as well as certain congenital conditions (see CONGENITAL CONDITIONS) of metabolism. Many metabolic diseases cause similar patterns of nonspecific abnormal bone growth (i.e., periosteal reactions) or bone reduction (i.e., pitting), complicating the identification of the specific metabolic disorder in skeletal remains. The metabolic diseases described in detail in the paragraphs to follow include those identified in past populations through their unique skeletal manifestations.

Vitamin C is an important nutrient in immune response, absorption of iron, and the formation and maintenance of body tissues, especially collagen. It must be obtained from dietary sources, such as fresh fruits and uncooked vegetables. Vitamin C deficiency is known as scurvy, the consequences of which are dependent upon the age of the individual and the duration of the deficiency. Several symptoms arise as a result of the impaired collagen formation associated with scurvy. These include hemorrhaging, hemarthrosis (bleeding into the joints), hair loss, and depressed osteoblastic activity. The skeletal manifestations of scurvy that are visible in human remains from archaeological sites vary according to the age of the individual. In subadult individuals, chronic bleeding from scurvy can cause abnormal porosity of bone cortex (particularly affecting the sphenoid, mandible, maxilla, orbits, scapulae, and os coxae), new bone formation (affecting the orbits, cranial vault, long bone ends, and os coxae), dental enamel hypoplasias and antemortem tooth loss, and enlargement or fracture of ribs near the costochondral

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junction. In adults, scurvy can result in new bone formation in the orbits and the ends of long bones, antemortem tooth loss and alveolar bone inflammation, vertebral osteopenia and possible biconcave compression, and transverse fractures of ribs at the costochondral junction (Brickley and Ives 2008).

Due to the role of vitamin C in iron absorption and its association with internal bleeding, scurvy and anemia (see ANEMIA) often exist as co-morbidities, complicating attempts to separate symptoms and skeletal effects caused by each condition. Similarly, scurvy's influence on immune system fitness leads to co-morbidities with infectious diseases that cause nonspecific skeletal reactions such as periostitis and osteomyelitis. Thus, a cautious approach must be taken in the paleopathology (see PALEOPATHOLOGY) of scurvy, including the description of a combination of probable scorbutic lesions, the weighting of the more unique lesions such as sphenoidal porosity, and the use of a rigorous differential diagnosis (see DIFFERENTIAL DIAGNOSIS). The use of scanning electron microscopy, for example, has been shown to successfully distinguish between the expansive *dipl e* of anemic orbital porosity and the periosteal reaction characteristic of scorbutic orbital porosity (Brickley and Ives 2006).

Evidence of scurvy has been reported at archaeological sites globally, including in areas with surprisingly ample dietary sources of vitamin C in the natural environment. These discrepancies between expected and observed nutrition of ancient populations have been attributed to the role of social control and structural violence influencing nutritional variation within and between populations, as well as nondietary factors such as infectious disease and parasitism (see PARASITOLOGY) (Halcrow et al. 2014). In these cases, paleoethnobotany and stable isotope (see PALEOETHNOBOTANY AND STABLE ISOTOPES) evidence of diet may serve to narrow the etiology of scurvy. However, these cases of the appearance of scurvy in unlikely environments speaks volumes to the potential underreporting of scurvy cases in paleopathology where mild scorbutic lesions may be disregarded or misinterpreted, and scurvy not considered in differential diagnoses. Due to the challenges surrounding scurvy's co-morbidities, its often nonspecific skeletal manifestation, and potential

for underreporting in the paleopathological literature, wider paleoepidemiological patterns of this metabolic disease in antiquity remain to be seen.

Vitamin D is necessary for immune reaction, mineral metabolism, cell growth, and cardiovascular health. It can be either produced by the body naturally through conversion of ultraviolet rays in the skin, or obtained through dietary sources such as dairy products. The deficiency of vitamin D, called either rickets or osteomalacia depending on the age of the individual, can cause hypocalcemia and poorly mineralized bone. As with scurvy, the skeletal manifestation of vitamin D deficiency varies according to the age of the person affected. In subadults, rickets causes delayed closure of fontanelles, thinned cranial bone, and frontal/parietal bossing, as well as layers of spiculated, irregular porous bone in the cranium. It also causes delayed dental eruption, hypoplastic defects, kyphosis or scoliosis of the vertebrae, enlargement of costochondral rib junctions and sternal protrusion, abnormal bending of the ribs, os coxae, sacrum, and long bones, and porosity, fraying, and enlargement of the metaphyses due to disorganized growth, which often leads to growth stunting. In adults, osteomalacia causes fine pitting of the cranium, antemortem tooth loss, kyphosis or scoliosis with biconcave compression of vertebral bodies, pseudofractures of the ribs and os coxae, long bones, scapulae, metacarpals, and metatarsals, and angulation or bending of the os coxae, long bones, scapulae, and ribs.

Evidence of rickets and osteomalacia has been reported at several archaeological sites, with most following the Industrial Revolution in the British Isles and northern Europe where manmade smog coupled with naturally limited sunlight during the winter months reduced the body's ability to manufacture vitamin D. As with scurvy, the effects of vitamin D deficiency on the skeleton are more severe in subadult individuals due to the mineral requirements of rapid bone turnover due to growth. The skeletal effects of rickets and osteomalacia may remain unnoticed in many cases, with very mild bending of the long bone shafts that only slightly enhances their normal bending morphologies. In environments allowing more ultraviolet ray exposure, these metabolic diseases of vitamin D deficiency may indicate cultural practices of prolonged breastfeeding (see

INFANT FEEDING) and inadequate exposure of high-social-class individuals to sunlight (Giuffra et al. 2015).

One of the most common metabolic diseases resulting from hormonal deficiency is osteoporosis. Osteoporosis describes a decrease in bone mass with subsequent increase in fracture risk associated with age-related decline in sex hormones of both men and women. Its skeletal manifestations include fine pitting, porosity, or thinning of the cranial vault, antemortem tooth loss or resorption of the alveolar margins, fractures of the vertebrae, ribs, pubic rami, distal radius, or femoral neck or trochanter, kyphosis, vertebral wedging, or biconcave deformities, and thinning of the ilia.

Osteoporosis can be difficult to identify with confidence in archaeological human remains. Several case studies have attributed skeletal changes to osteoporosis, but few studies have surveyed its presence at a populational level. Differential diagnosis of osteoporosis in paleopathology is complicated by its co-morbidity with scurvy and vitamin D deficiency, as well as its sometimes subtle skeletal manifestation (i.e., generally lightweight bones or noticeably dispersed trabeculae). Such a wider populational study could reveal influences of diet and activity level as evidenced by susceptibility to osteoporosis.

Paget's disease of bone refers to a chronic disease resulting in the disruption of bone remodeling in certain bones, characterized by skeletal enlargement. The cause of the disease is still uncertain, but it seems to have a genetic and perhaps infectious (viral) component. Its skeletal manifestations include enlargement or thickening of the cranial vault and vertebrae, hypercementosis or ankylosis of the teeth, fractures of vertebrae and long bones, deformities of the os coxae, bowing or widening of the long bones, and a bone surface texture similar to that of pumice stone.

Paget's disease of bone has rarely been identified in archaeological human remains, including at many sites in the British Isles, leading to the hypothesis that this disease originated in the region. Again, paleopathological reports of this metabolic disease have mainly consisted of case studies, with population-level prevalence unknown. Co-morbidities such as osteosarcoma co-occurrence with Paget's disease of bone are

likewise unexplored in past populations. With more regional surveys and meta-analyses, bioarchaeologists are poised to offer key details of the potential environmental and genetic factors that play a role in the disease.

Fluorosis is a condition caused by the surplus of fluoride in the body due to the ingestion of toxic levels. Fluorine substitutes for the hydroxyl ion in the hydroxyapatite crystal of bone and teeth, forming fluoroapatite, a more brittle structure. Fluorine also stimulates osteoblastic activity. The skeletal manifestation of fluorosis includes thick, heavy, and irregularly shaped bones (particularly the cranium and long bones), ossification of soft tissue attachments, ankylosis of the vertebrae and ribs, and teeth with white patches and possible pitting.

Fluorosis has been reported from archaeological sites in North America and the Middle East. Again, careful differential diagnosis considering combinations of skeletal lesions and the inclusion of environmental and epidemiological evidence is necessary to pinpoint fluorosis in past populations. With advances in human skeletal geochemistry (see HUMAN SKELETAL GEOCHEMISTRY) and portable X-ray fluorescence spectrometry (pXRF) (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)), future analyses of fluorosis and other metabolic conditions may be bolstered by trace element analysis of bone, though caution must be taken to rule out confounding factors of postmortem mineral absorption from the soil.

Other, less common metabolic conditions include hyperparathyroidism, pellagra, starvation, hyperostosis, hypophosphatasia, osteogenesis imperfecta, and osteopetrosis. These conditions are not discussed here due to the rarity of their detection in human skeletal remains. Much is still unknown about the mechanisms and skeletal manifestations of metabolic disorders. With advances in clinical knowledge of the biological processes and effects of various chemicals on metabolism, bioarchaeologists will be able to identify more skeletal manifestations of metabolic disorders in osseous remains. Many metabolic bone diseases have overlapping skeletal manifestations, necessitating the use of multiple lines of evidence and differential diagnosis. With increased calls for increases in rigor in paleopathology, use of algorithmic methods

to account for lesion patterning in differential diagnosis, and incorporation of advanced imaging and mineral composition assays, metabolic bone disease is poised to feature more widely in future studies of skeletal pathologies and lifelong skeletal maintenance and well-being in past populations.

SEE ALSO: Malnutrition

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FURTHER READINGS

Mobility and Lead Isotopes

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In recent years, lead (Pb) isotope ratios have become an increasingly powerful tool to track mobility in the archaeological record. Much like strontium, lead isotopic testing compares isotope ratios from human and other animal remains to known ratios in the bedrock of a geographic area as a means of identifying the place of origin of the individual. Combined with other sourcing techniques, lead isotope analysis allows archaeologists to more accurately identify where on the landscape a human or other animal moved during its life, providing archaeologists with an enhanced means of exploring such topics as seasonal mobility, immigration, exchange, communication, and other social relationships between regions. Isotopic detection of such activities is particularly useful among ancient societies that lacked written records that would otherwise attest for such movements.

Biogeochemistry of lead isotopes

There are three isotope ratios of lead that are commonly used in archaeology: $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$, and $^{208}\text{Pb}/^{204}\text{Pb}$. ^{204}Pb is a nonradiogenic isotope, while ^{206}Pb and ^{207}Pb are the radiogenic products of uranium decay (^{238}U and ^{235}U , respectively), and ^{208}Pb is the product of thorium (^{232}Th) decay. Lead isotope ratios in bedrock are determined by the original amounts of U, Th, and Pb in the rock, as well as the elapsed time since the rock formation. Unlike strontium and oxygen isotopes that are also used for tracing

mobility, lead isotope ratios in living organisms are not influenced by coastal ocean spray.

Although still not clearly defined, the most probable pathway for lead incorporation into animals, including humans, is through ingestion and/or respiration of dust and soil from the surrounding environment. Lead is incorporated into the skeletal tissues of animals, including teeth and bones. Unlike isotopes with lighter atomic masses, such as carbon and oxygen, lead isotopes do not fractionate, or separate by isotopic mass, in living organisms. Thus, the lead isotopic ratios in the bedrock of a region reflect the ratios in the skeletal tissue of an animal that lived in that region. Analysis of the lead ratios in tooth enamel apatite, which forms early in an animal's life, and unlike bone does not remodel later in life, can help identify the animal's place of birth. Similarly, bone tissue remodels over time, and so by testing the lead ratios in bone apatite, archaeologists can identify the lead isotope ratio average from the last few years of an animal's life. However, a major obstacle for using archaeological bone in lead isotopic studies is the possibility of postmortem diagenetic alteration (see *DIAGENESIS OF BONE*), such as from chemical changes brought on by extended contact with the surrounding soil. Enamel is a much denser substance, and its isotopic composition is less susceptible to diagenesis than bone. Because enamel in human teeth develops at different times during childhood and adolescence, comparing the lead isotope ratios between different eruption stages (i.e., first through third molars) can detect whether an individual moved to different locations during different stages of their youth.

Methods

The process of lead isotopic testing bears similarities to that of strontium, and the two can be tested from the same prepared sample. The extraction process from bone or enamel apatite takes place in a clean laboratory setting, minimizing the

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risk of contamination from modern lead in the environment. The lead isotopes in a sample are separated using an ion chromatography procedure, and are thereafter measured using either a thermal ionization mass spectrometer (TIMS) or, preferably, a multicollector inductively coupled plasma mass spectrometer (MC-ICP-MS) (see ICP-MS AND MATERIAL ANALYSIS). NBS 981 is used as the standard for reproducibility.

Anthropogenic lead

Archaeologists who use lead for isotopic sourcing must be wary of contamination from modern anthropogenic lead. This may occur in the form of modern lead pollution; for example, archaeological human and other animal bones located near the surface of an urban area or near a location where leaded gasoline had been used, such as a road, might become contaminated with anthropogenic lead. Similarly, lead baseline studies should avoid using modern soil or plants, since these have high potential for contamination from anthropogenic lead. Bedrock is much more reliable for establishing baselines that can be applicable to the archaeological record, and archaeological soils may also contribute towards this end.

Applications

Lead isotope mobility studies have been used with increasing frequency now that there are more regional baseline maps available, developed by geologists and archaeologists alike. Many of these studies have been conducted in Europe, examining movements of humans throughout the Roman Empire and especially Great Britain (e.g., Shaw et al. 2016). In the Indus Valley region of Pakistan and northwest India, lead isotopes have been used to track the movement of adolescents as they migrated from rural to urban areas and between urban centers as a means of solidifying ties between developing communities over time (Valentine et al. 2015). Lead baseline studies are currently underway in Central America and the Andes as a means to investigate human and animal movements and exchange systems (Sharpe

et al. 2016; Turner et al. 2009). In the Caribbean, lead isotopes have been used in combination with strontium to track the introduction of animals to different islands by humans (Giovas et al. 2016). Some investigations have even made use of anthropogenic lead to track mobility, particularly studies detecting individuals in a population that may have been subjected to smelting activities, such as miners and metallurgists (Price et al. 2017). Lead isotopes are especially useful in tracking the introduction of metal smelting technology, particularly lead and silver, across different regions over time.

Lead isotope analysis has been used to track human mobility in modern forensic cases as well. Human skeletal remains recovered from the last century commonly exhibit modern lead isotope ratios derived from the leaded gasoline used in the individual's country of origin (Kamenov and Gulson 2014). Furthermore, twentieth-century human teeth show distinct lead isotope ratios when compared to archaeological populations from the same region. The natural lead isotope background in a given region can be rapidly altered once humans begin to mine and use lead. Therefore, in certain instances, archaeologists may need to use lead isotope data from ore deposits mined in antiquity as a baseline for tracking human mobility in the past.

SEE ALSO: Human Skeletal Geochemistry; Isotopes; Mobility and Oxygen Isotopes; Mobility and Strontium Isotopes; Zooarchaeology and Human Trade and Migration; Zooarchaeology and Stable Isotopes

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Mobility and Oxygen Isotopes

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Stable oxygen isotopes have great utility in archaeological provenience studies due to the high degree of geographic patterning in isotopic distributions. Heavier isotopic species of oxygen (^{18}O versus ^{16}O) are discriminated against during changes of state reactions in water (see ISOTOPES). This means that isotopic fractionation (differential rate of reaction by isotope mass) occurs during the production of water vapor from liquid water and vice versa, and the natural distribution of the isotopes of oxygen is a result of the balance of evaporation and condensation. In the hydraulic cycle, the majority of meteoric water evaporates from the ocean near the equator, providing a baseline oxygen isotopic ratio, and depletion of ^{18}O occurs as this water vapor condenses during precipitation and re-evaporates. The stable isotope ratio of water is reported in terms of $\delta^{18}\text{O}$, or the $^{18}\text{O}/^{16}\text{O}_{\text{sample}}$ ratio by departure from standardized ocean water $^{18}\text{O}/^{16}\text{O}$, measured in units permille (‰). Isotopic ratios in precipitation become progressively lower with distance from main water sources as the heavier isotope “rains out.” Since colder air has a reduced carrying capacity, increased altitude and latitude also result in lower isotopic ratios. A worldwide network of meteorological stations has measured the isotope values in monthly precipitation since the 1960s and summarizes this spatial variability (IAEA/WMO 2017).

This patterning allows one to discriminate among locations with broad climatic differences, meaning that stable oxygen isotopes act as a biological tracer. Often, yearly average $\delta^{18}\text{O}$ values in rainwater can be used to estimate the isotopic composition of local drinking water. In mammals, body water $\delta^{18}\text{O}$ ($\delta^{18}\text{O}_{\text{bw}}$) is primarily governed by water intake and thus directly

reflects the values in precipitation. After oxygen is taken up in drinking water, metabolic functions incorporate it into different tissue types such that their $\delta^{18}\text{O}$ values are characterized by that of body water (Koch 2007).

In archaeological samples, original isotopic values are often retained in carbonate and phosphate of enamel and bone, resulting in their use as a geographic provenance indicator (Koch 2007) and in paleoclimatology. Other biological tissues, such as hair and fingernails, may also be analyzed from mummified remains. In skeletal tissue, phosphate comprises a large component of the mineral phase of bone or apatite ($\text{Ca}_{10}[\text{PO}_4]_6[\text{OH}]_2$) and carbonate substitutes for hydroxyl and phosphate groups (LeGeros 1981). The overall precision of phosphate in discriminating between water sources may be better than that of carbonate, and phosphate is also considered more resilient to inorganic alteration. However, carbonate may be more resistant to microbial alteration and its treatment and analysis is relatively easier and lower in cost.

Analysis of different tissues yields $\delta^{18}\text{O}$ values that reflect when these tissues formed during an individual's lifespan (see HUMAN GROWTH AND DEVELOPMENT and DENTAL DEVELOPMENT). Since cortical bone remodels over time, bone $\delta^{18}\text{O}$ slowly changes in response to local conditions and may provide an estimate of geographic residence near time of death. Enamel does not remodel and reflects the geochemical signature of an individual's place of residence during childhood development of the enamel crown. Thus, it may be possible to detect shifting geographic residence patterns by analyzing bone(s) and enamel in tandem from a single skeleton. Alternatively, since enamel formation is an incremental process, sequential samples from enamel layers or different teeth may be used to characterize seasonal movement in highly mobile populations.

Methods

Sample treatment differs for bone versus enamel, since alteration of the chemical composition of

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apatite is reduced in enamel and contaminants from the burial environment are more easily removed from this material (see *DIAGENESIS OF BONE*). The sample amount required for analysis is also tissue specific, and broadly based on estimates of molecular content per weight-percent (LeGeros 1981). An isotope ratio mass spectrometer (IRMS) measures oxygen isotope ratios in samples, and reports $\delta^{18}\text{O}$ relative to a material-specific standard (see *MASS SPECTROMETRY (MS)*). Common methods of diagenesis monitoring include obtaining the concentrations of trace elements often introduced into or leached out of bone or enamel during chemical alteration, or identifying postmortem changes in apatite crystallinity.

Defining local ranges

Isotopic results are compared to expected values through use of conversion equations. Isotopic spacing between body water and phosphate and the offset between $\delta^{18}\text{O}$ in phosphate and $\delta^{18}\text{O}$ in carbonate are linear. These relationships are assumed to be stable since carbonate and phosphate are thought to precipitate from the same body water pool with a constantly renewed and therefore constant $\delta^{18}\text{O}_{\text{bw}}$ value (France and Owsley 2015; Daux et al. 2008). The resulting conversion equations allow direct comparison of archaeological populations, or conversion of $\delta^{18}\text{O}$ from biological tissue to $\delta^{18}\text{O}_{\text{bw}}$. This value can then be compared to the modern isotopic composition of rainwater as interpolated by models accounting for latitude, longitude, and elevation (IAEA/WMO 2017).

However, the local range in $\delta^{18}\text{O}_{\text{bw}}$ is unlikely to exactly match local meteoric water $\delta^{18}\text{O}$, making it imperative that samples accurately represent the “local” $\delta^{18}\text{O}$ signal in biological tissue. In some cases, this discrepancy is due to averaging effects, for example, seasonal rainfall patterns may determine the $\delta^{18}\text{O}$ of drinking water, or humans may consume foods grown or foddered from a variety of local environments. In modern humans, variability in isotopic ratios is thought to be dependent on geography as well as human behavior (Daux et al. 2008). High mobility in an alpine area may result in high standard deviations

for “local” $\delta^{18}\text{O}_{\text{bw}}$. For archaeological samples, a conservative range of 2‰ has been traditionally used to represent nonmobile populations, but this range can also be determined using the distribution of experimental data (Wright 2012). For this method, a population sharing the same water source should display a normal distribution in $\delta^{18}\text{O}$ values as incorporated into body tissue, and any migrants will be statistical outliers. These methods for migrant identification depend, however, on the geographic origin of nonlocals being isotopically distinct from that of locals.

Cultural practices

Overlapping local ranges due to similar climatic conditions, high local mobility, and dietary or cultural practices may all preclude migrant identification. The use of open containers for storing drinking water allows evaporation and lead to enrichment in the heavier isotope of oxygen. The practices of brewing or stewing enhance this fractionation effect (Brettell, Montgomery, and Evans 2012). Consumption of processed fruits such as in olive oil or wine may also cause enrichment in ^{18}O (see *PALEOETHNOBOTANY AND STABLE ISOTOPES*), and when imported these products retain the $\delta^{18}\text{O}$ signature of their geographic origin. These cultural practices may significantly impact the $\delta^{18}\text{O}_{\text{bw}}$ in archaeological samples.

Breastfeeding may also result in enrichment of the oxygen isotopic composition of enamel. Since human societies conclude weaning at different ages (see *INFANT FEEDING*), this means that the $\delta^{18}\text{O}$ of enamel mineralized during early childhood may reflect the $\delta^{18}\text{O}_{\text{bw}}$ of the mother in addition to the $\delta^{18}\text{O}$ of local drinking water. Oxygen isotopes may thus be used to track the onset of weaning in a population, and tooth choice is an important factor in mobility studies.

The sensitivity of $\delta^{18}\text{O}$ to both geographic location and cultural factors makes it a powerful tool in human mobility research. Both bones and teeth regularly retain oxygen isotopic ratios which reflect geographic patterning, and many analytical methods are available for their study. Limitations in this isotopic tracer may be avoided by sample choice, and by combining oxygen isotope analysis with other isotopic systems,

such as lead (see MOBILITY AND LEAD ISOTOPES), strontium (see MOBILITY AND STRONTIUM ISOTOPES), or trace elements. These geochemical characterizations of geographic origin in mobility studies form an important component in understanding ancient life histories.

SEE ALSO: Diet and Nitrogen Isotopes

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Mobility and Strontium Isotopes

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Reconstructing the mobility patterns of archaeological populations is a challenging task that many traditional avenues of inquiry cannot directly address. Radiogenic strontium isotope analysis ($^{87}\text{Sr}/^{86}\text{Sr}$) offers a direct way to analyze mobility using the isotopic composition of human skeletal remains. Since the introduction of $^{87}\text{Sr}/^{86}\text{Sr}$ analysis in archaeology by Ericson (1985), this technique has been widely applied to examine the movement of past groups in past societies throughout the world. Current research uses radiogenic strontium isotopes to examine population dynamics, exchange, conflict, sociopolitical organization, and cultural interactions. Beyond assessments of human mobility in the past, researchers also use $^{87}\text{Sr}/^{86}\text{Sr}$ to study the movement of fauna, artifacts, and food recovered at archaeological sites. Currently, most mobility studies on archaeological populations use strontium isotope analysis of bones and teeth in conjunction with other isotopes such as oxygen and lead (see MOBILITY AND LEAD ISOTOPES and MOBILITY AND OXYGEN ISOTOPES). In areas with regionally diverse diets, stable carbon and nitrogen isotopes have also been used with strontium data to obtain nuanced interpretations of mobility patterns (see DIET AND CARBON ISOTOPES and DIET AND NITROGEN ISOTOPES).

Strontium is an alkaline earth element that has four naturally occurring isotopes: ^{84}Sr , ^{86}Sr , ^{87}Sr , and ^{88}Sr . One of these isotopes, ^{87}Sr , is radiogenic and forms from the radioactive decay of rubidium (^{87}Rb), which has a half-life of 4.88×10^{10} years (Faure and Mensing 2005). The ratio between ^{87}Sr and ^{86}Sr (written as $^{87}\text{Sr}/^{86}\text{Sr}$) is of interest to mobility researchers because it is patterned geographically due to underlying geologic differences in the ratio of Rb/Sr and the ages of the rocks. Very old rocks with a high original Rb/Sr

ratio will have higher $^{87}\text{Sr}/^{86}\text{Sr}$ values, while younger rocks with low Rb/Sr ratios have lower $^{87}\text{Sr}/^{86}\text{Sr}$ values (Faure and Mensing 2005). These base differences in $^{87}\text{Sr}/^{86}\text{Sr}$ are incorporated into soils and groundwater via weathering processes. Strontium subsequently enters the food web with negligible biological fractionation, such that the foods and water in an area will have an $^{87}\text{Sr}/^{86}\text{Sr}$ value broadly consistent with the local geology.

Upon entering the body from food and water, the majority of strontium in the body is stored in the mineral component of bone, called hydroxyapatite, where strontium substitutes for calcium. Overall, less strontium is absorbed than calcium relative to what is available in the diet, a process called biopurification. This effect is magnified moving up trophic levels, such that carnivores have lower Sr/Ca than do plants and herbivores. The net result of this process is that the variance of $^{87}\text{Sr}/^{86}\text{Sr}$ is reduced in skeletal remains compared to soils and plants, and the $^{87}\text{Sr}/^{86}\text{Sr}$ of skeletal tissue reflects an average of dietary intake as the tissues develop. Thus, the $^{87}\text{Sr}/^{86}\text{Sr}$ of human remains is determined by the $^{87}\text{Sr}/^{86}\text{Sr}$ of items consumed, which in turn reflect the local geology, allowing for reconstructions of paleomobility (Bentley 2006; Ericson 1985).

When dealing with skeletal collections, there are two tissues available for strontium isotope analysis: dental enamel and bone (see HUMAN SKELETAL GEOCHEMISTRY). Human dental enamel forms during childhood and does not remodel during the lifetime of an individual. As a result, the $^{87}\text{Sr}/^{86}\text{Sr}$ of an individual's enamel represents their geographic location while the enamel was forming. The final teeth to develop in humans, third permanent molars, complete amelogenesis around age 13 years, so the $^{87}\text{Sr}/^{86}\text{Sr}$ of enamel represents an individual's location during childhood. In contrast, human bone is constantly remodeling such that the $^{87}\text{Sr}/^{86}\text{Sr}$ of bone reflects an individual's place of residence prior to their death. The tissue selected for analysis often depends on concerns about diagenesis (post-depositional chemical alteration of the tissue). In areas with poor preservation,

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researchers often choose to only sample enamel to ensure the integrity of their data (Wright 2005). Alternatively, researchers can sample both tissue types to compare the geographic location of an individual during childhood versus the last years prior to death (Ericson 1985). This latter type of analysis allows for a nuanced look into mobility patterns over the lifetime of an individual.

With increasing use of strontium isotopes to reconstruct mobility, researchers have also identified several challenges to $^{87}\text{Sr}/^{86}\text{Sr}$ studies. One of the primary difficulties researchers encounter when analyzing strontium isotope data is the establishment of a “local” range of $^{87}\text{Sr}/^{86}\text{Sr}$ values for a given archaeological site. The soils in an area can vary substantially in $^{87}\text{Sr}/^{86}\text{Sr}$ values depending on the mineral composition of the soil, differential weathering patterns, water movement, and other environmental influences on individual minerals in the soil. Thus, it is difficult to use the $^{87}\text{Sr}/^{86}\text{Sr}$ of soil to establish a local strontium signature (Price et al. 2002). However, although local soils can have variable strontium isotope values, faunal skeletal remains often have homogeneous $^{87}\text{Sr}/^{86}\text{Sr}$ values due to averaging of local variability within the animal’s grazing range that allow researchers to establish a local $^{87}\text{Sr}/^{86}\text{Sr}$ range. Price et al. (2002) suggest using small-bodied animal remains to gain a baseline $^{87}\text{Sr}/^{86}\text{Sr}$ range for assessing human mobility patterns rather than referencing local geologic substrates directly. In the absence of faunal data, researchers have also looked to the statistical distribution of human $^{87}\text{Sr}/^{86}\text{Sr}$ values to define a local $^{87}\text{Sr}/^{86}\text{Sr}$ range (Wright 2005). Identifying a local strontium signature in this manner assumes that the local population was primarily consuming food and water from nearby sources and did not heavily rely on imported foods which might have a very different $^{87}\text{Sr}/^{86}\text{Sr}$ value.

In addition, the precise identification of a place of origin for migrants is frequently impossible using $^{87}\text{Sr}/^{86}\text{Sr}$ data alone. Quite disparate geographic regions can have identical $^{87}\text{Sr}/^{86}\text{Sr}$ values, limiting the precision with which researchers can identify nonlocal people. However, using additional isotopes such as stable oxygen, lead, carbon, and nitrogen isotopes in conjunction with strontium data allows for

greater identification of mobility patterns in ancient populations (Knudson and Price 2007).

Since the introduction of $^{87}\text{Sr}/^{86}\text{Sr}$ analysis in archaeology, researchers have made substantial contributions to understanding ancient mobility patterns, although there is ample room for future research. Traditional sampling strategies require 5–20 mg of bone or enamel, limiting the application of isotopic analysis on sensitive or rare specimens, such as early archaeological sites or fossil remains. New techniques, such as sampling via laser ablation, substantially limit the destructive nature of isotopic analysis, potentially providing new arenas in which these techniques could be applied (Copeland et al. 2008). In addition, the geographic distribution of $^{87}\text{Sr}/^{86}\text{Sr}$ values is largely unknown for many regions of the world. Further documentation of $^{87}\text{Sr}/^{86}\text{Sr}$ values will greatly enhance the utility of this isotope for reconstructing mobility in archaeological populations. Furthermore, the $^{87}\text{Sr}/^{86}\text{Sr}$ of different foodstuffs is poorly documented. A better understanding of the $^{87}\text{Sr}/^{86}\text{Sr}$ in likely dietary items could help elucidate $^{87}\text{Sr}/^{86}\text{Sr}$ patterning in archaeological populations.

SEE ALSO: Isotopes

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Mortuary Analysis

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It is an often repeated observation that there is more anthropological information per cubic meter of a human burial than any other type of archaeological feature. However, with this density of data come interpretive hurdles. The characteristics that make human mortuary deposits rich sources of information about past societies are inherent in an archaeological feature with both biological and sociocultural content. Thus it is not surprising that the ways archaeologists have interpreted data recovered from human burials is similarly complex. Data from burials have been examined for answers to some of the key questions prehistorians have asked and mortuary analysis has figured prominently in debates between scholars. As the goals of theoretical paradigms in archaeology have differed, so too have the ways researchers utilized mortuary data. At various times the focus has been on reconstructing ancient social structure and organization. At other times, interpreting the ideological or religious meaning behind various treatments has been paramount. Thus the various approaches to mortuary analysis have tracked the ebb and flow of theoretical developments within archaeology. Moreover, human burials have figured prominently in recent interactions between descendant communities and archaeologists.

In the United States, mortuary analyses were initiated by none other than Thomas Jefferson, who trenched a Native American burial mound near his home at Monticello (probably in 1783). The purpose of his excavation was to determine the manner by which the mound, and others like it, was constructed. Differences in the observed strata, superposition of materials, and the arrangement of skeletal remains indicated to him that the mounds were formed by accretion as the community interred their dead over time. Jefferson's approach has been

lauded as an early example of problem-oriented, careful archaeological excavation designed to test hypotheses and an approach that would easily be described as mortuary archaeology.

In Europe, during the late eighteenth and early nineteenth centuries, mortuary analysis was used in the development of chronological schemas. The antiquarianism of the late eighteenth century included a growing interest in graves. Hundreds of barrows and burial mounds were excavated. Analyses involved developing typologies of graves and chronologically sorting them on the basis of stratigraphy and an early form of relative dating. Christian Thomsen, a Dane, was able to refine chronologies through the examination of what he called "closed finds." These were assemblages of artifacts from features, frequently burials, which could be presumed to have been deposited at a single point in time. The Scandinavian chronologies developed by Thomsen and his student Jens Worsaae and the techniques that produced them were later extended across Europe. W. M. F. Petrie used a similar technique for sorting hundreds of Pre-Dynastic graves on the basis of changes to pottery form and design. In the early twentieth century, the analysis of burials for purposes of constructing chronologies was continued by culture-historians in the Americas. For example, Alfred Kidder used burials recovered at Pecos Pueblo to help define and refine his chronological sequence. Chronology was the focus of both Old and New World prehistorians and would remain so until basic culture-historical sequences of the various culture-areas were established.

The 1960s processual "New Archaeology" revolution ushered in an ambitious approach to human burials (Brown 1971). Sometimes referred to as the "representationalist" approach, processualists sought to reconstruct the social status of the deceased and in doing so assess the sociocultural complexity of the community. The approach assumed that the deceased's status was mirrored or "represented" in their mortuary treatment, particularly in the quantity and quality of grave offerings and energy expended on the burial. The more lavish the offerings, the higher

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the status of the individual. Cemetery samples containing a range of offerings suggested social hierarchies, while those containing no variation indicated egalitarian societies. Scholars following this approach often use statistical clustering techniques to examine mortuary data for evidence of hierarchy. This perspective continues to be utilized by archaeologists to make claims about social organization in prehistoric communities and there are reasons to expect that in some contexts these claims are correct.

In the 1980s, mortuary analysis was one of the battlefields for the postmodern critique of the processual approach. These post-processualists used ethnographic and historical examples to demonstrate that there are contexts where mortuary practices are not a simple reflection of social statuses. In these cases, expenditures on the grave are not isomorphic with the deceased's status and sometimes diverge drastically from it. These divergences occur because the dead do not bury themselves but rather are buried by the living who use the occasion of a death as an opportunity to communicate and negotiate among themselves. Post-processualists advocated for the contextual, interpretive "reading" of burials as meaningfully constituted cultural texts. Further, this viewpoint on mortuary data foregrounds the mortuary rite as a performative event that is used for social and/or political machinations and to convey information.

Adding a diachronic perspective to mortuary analysis, Aubrey Cannon (1989) provided case studies which demonstrated that funerary treatments can oscillate from periods of high elaboration to periods with more understated displays. These cycles of ostentation occur as social groups appropriate the funerary practices of other groups as a way of appropriating their class or cultural identity. In response, the mimicked group will abandon their traditional practices for an alternative one in an effort to maintain a clear distinction. Further mimicking follows, leading to adoption of new practices and so on. This cyclical process explains why mortuary practices provided such useful chronological markers for the antiquarian and culture-history archaeologists. It also explains why in some cases the processual viewpoint is applicable and why in others it is not.

In some regards, the Marxist approach is an extension of the post-processual movement in that it recognizes mortuary treatments as enactments of and by society that may not faithfully mirror social, economic, or political reality. Burials, from a Marxist point of view, represent deposits of social labor. Deployment of surplus labor in mortuary contexts might indicate status inequality or it may mask that inequality. Moreover, different objects or treatments used within a burial may have different social value on the basis of the labor needed to produce them. Therefore, Lull (2000), for example, recommends a comparison of consumption of products in nonmortuary contexts versus the funerary context in order to elucidate socioeconomic and socio-ideological structures within the society.

In the 1990s, a new interest in ancestors and ancestor-hood emerged in the archaeology of death. Inspired by the work of Max Gluckman, Robert Hertz, Arnold Van Gennep, Ian Morris, Richard Huntington, and Peter Metcalf, mortuary analysts began to focus on how "ancestors" differ from simply the dead. This approach recognizes that in many societies death does not automatically confer ancestor-hood on an individual. Indeed, Gluckman makes a distinction between "cults of the dead" which represent rites of passage marking the transition from life to death and "ancestor cults" which establish someone as an ancestor with an active role in the lives of the living. Examinations of postmortuary rituals and evidence of continued interactions with the deceased continued into the 2000s and were supplemented by other topics. These included explorations of mortuary rituals and their role in social memory, identity and personhood, gender and age, embodiment, and the location (space and place) of burials. Throughout the 1990s and 2000s, the overarching guideposts for mortuary analyses included the heavy use of ethnographic data to inform interpretations of archaeological cases, an acknowledgment of the agency of the living in dealing with the dead, and a recognition that mortuary practices are performative (Rakita and Buikstra 2005).

The second decade of the new century has seen two significant developments in mortuary analysis. The first is a re-emphasis on the importance of detailed observation of in-situ materials

and a clarification of terminology used to make those observations. Knüsel (2014) described archaeothanatology, an approach advocated by Henri Duday that involves the careful excavation, recording, and analysis of human skeletal remains in order to identify signs of funerary behavior and taphonomic processes. Where the archaeothanatomical approach is particularly useful is in focusing attention on the careful excavations and observations that can tell us about the processes that happened from the moment of interment to the moment of excavation. Reconstructing this process should allow for better reconstruction of the moment of the burial (which has considerable cultural content).

The second development is a trend towards greater integration of mortuary and bioarchaeological data. Processual archaeology and its more optimistic view of mortuary analysis was an important influence on the development of bioarchaeology (see BIOARCHAEOLOGY) which itself has had a significant impact on the amount of information gleaned from skeletal remains from mortuary contexts. However, for decades, consistent and deeply integrated analyses of data from both mortuary contexts and human remains were rare. More recently there has been greater emphasis on comparing archaeological derived data with information gleaned from osteological analyses. For example, Quinn and Beck (2016) recommend comparisons of mortuary and bioarchaeological data to assess coherence between lived and performed identities. They explore the interpretive possibilities of coherence between archaeological and biological signatures of inequality (interpreted as institutionalized inequality) and equality (interpreted as egalitarian contexts). Alternatively, dissonance between the two datasets might indicate mortuary practices that mask lived inequality or mortuary practices that exaggerate inequality that may not have been as extreme for the living.

Increased engagement with the ethnographic literature on mortuary practices has also led to a greater awareness of the importance of the dead in the lives of the living. Burials are important to descendant communities and this has played out in the political arena (Kakaliouras 2008). Many feared that the passage of the Native American Graves Protection and Repatriation Act (NAGPRA) would sound a death knell for

mortuary studies. And while excavations of large numbers of burial features have become rare in the United States, there has been a remarkable upswing in bioarchaeological publishing (Rakita 2014) possibly due to the publication of the “Standards” for collecting data from skeletal remains (Buikstra and Ubelaker 1994) and the recordation process mandated by NAGPRA. Thus, far from deterring bioarchaeological work in the United States, NAGPRA has ushered in an era of growing application of bioarchaeological methods to examine prehistoric and historic human populations. Intriguingly, NAGPRA has also encouraged archaeologists to regard human remains and their associated artifacts as inseparable and equally important components that must be cared for together. The Act has led to greater collaboration between mortuary analysts, bioarchaeologists, and descendant communities.

SEE ALSO: Bodies and Embodiment; Burial Excavation; Commingled Human Remains; Diagenesis of Bone; Embalming; Embodiment; Human Lives and Deaths; Osteology

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Musculoskeletal Stress Markers

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A great deal of effort has been put into reconstructing the daily life and physical activities of past populations in both physical anthropology and bioarchaeology. Researchers have long been interested in identifying occupational specialization by analyzing skeletal remains. Hawkey and Merbs (1995) used the term musculoskeletal stress markers (MSMs) to refer specifically to distinct changes at sites where muscles, tendons, ligaments, and cartilage attach to bone. The scores for MSMs, which range from 1 to 6, are based on the complexities of the surface shape at each attachment site, and are used for statistical analyses. It is important to compare differences in the patterns and profiles of MSMs using multivariate analysis, line graphs, and frequency distribution. These comparisons reveal differences in physical activity from the differences in MSM scores. All studies on MSMs have essentially been based on the principle of bone functional adaptation; that is, bone form reflects the cumulative effects of intra vitam mechanical loading or strain. Recently, the more neutral term “entheseal changes” was adopted at a workshop on MSMs that was held in 2009 at the University of Coimbra in Portugal. This neutral term was suggested to alleviate doubt regarding the correlation between MSMs and physical activities. Although the standards created by Hawkey and Merbs (1995) make it possible to rank scores based on entheseal severity, many researchers are often criticized for not taking into consideration the histology and organization of MSMs. The Coimbra group proposed a new scoring method based on the current understanding of the etiologies associated with these osseous changes. Entheses are now classified as either fibrocartilaginous or fibrous entheses according to the tissue type. The Coimbra group distinguished two

histological zones between the margin and the rest of the enthesis at each attachment site, and listed the alterations and features visible in each zone. This method has an advantage in that intra- and interobserver errors are small; however, the data cannot be ranked.

For both scoring methods, caution is warranted because similar scores at different sites do not necessarily imply similar degrees of exposure to biomechanical stress. One solution is to compare the patterns and profiles of MSMs using multivariate analysis and line graphs. MSMs scored using the Hawkey and Merbs method were the first to reveal unique MSM patterns of watercraft-using fishermen in various populations. Further, MSMs clearly correlate with the lifestyles based on socioeconomic status in a hierarchical society (Yonemoto 2016). This finding indicates that the effect of social hierarchy is manifested in MSMs, because lifestyles are regulated according to hierarchy.

However, many researchers still have questioned the validity of their correlation with physical activity, because MSMs are affected by various factors, including age, sex, and body size. These studies that have examined MSMs have several shortcomings. Many of these studies were conducted using only aggregate MSM scores. These scores only indicate whether the applied load was large or small. Although aggregate measures may be useful for reducing the error range and enhancing methodological validity, similar scores at different sites do not necessarily imply similar degrees of exposure to biomechanical stress. The aggregate scores could potentially prevent entheseal changes from being used as an indicator of the different ways past populations moved their bodies.

Moreover, age, and not physical activity, has been identified as having the highest correlation with entheseal changes. This age correlation could be related to the stresses that accumulate over the course of an individual's life. While this may be true, age cannot be regarded as the only factor that affects MSMs. Yonemoto (2016) noted that the degree to which age affects MSMs is dependent

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on cultural, social, and subsistence activities. This means that differences can be attributed to age group, as the chronological age of an individual in these societies likely contributed towards activities performed by that individual. Sex has been identified as having a high correlation with enthesal changes. The degree to which sex affects MSMs might also be population-specific, like the effects from age, because the activities of men and women are regulated by sexual division of labor.

The biggest challenge facing MSM studies is linking specific skeletal conditions to the development of attachment sites. Identical MSMs on skeletal remains from different locations are often ascribed to different physical activities; therefore, studies of MSMs are criticized as being “just-so stories.” It is impossible to understand a person’s life based only on a specific activity because all human life is a series of complex physical activities. Researchers should not be quick to assume that a similarity in MSMs among different populations points toward commonality in their physical activities.

Then what are MSMs useful for? It is necessary to examine the differences in the physical activities among social divisions and how age and sex affect MSMs. Furthermore, the degree of differences in MSMs among social groups should be compared between societies with different social organization, such as egalitarian, stratified, and hierarchical societies. In doing so, it may be possible to distinguish, for example, a skilled producer and an aristocrat from laborers. Such studies are meaningful because they relate to the

historical development of social inequality. The differences in these social divisions expressed by physical activities among various groups should be examined. By examining the differences in behavior patterns, MSMs may be a promising means for revealing correlations between characteristics of behavior patterns and social structure.

SEE ALSO: Bioarchaeology; Osteology

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Oral Health

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The oral health of past populations is of interest to archaeologists because it involves both biological and behavioral factors. Anthropologists focus on cultural and behavioral variables affecting oral health. These include subsistence, food choice, and food processing methods. Sex and social status differences in food type and frequency of consumption also affect dental disease rates. By contrast, biological forces affecting oral health include the nutritional value and chemical composition of food. The biology of sex impacts oral ecology by causing differential susceptibility to dental disease in men and women. The World Health Organization (WHO) International Classification of Disease lists 14 diseases of the oral cavity. Because teeth preserve well in archaeological samples, many pathological dental conditions are easily observed in calcified tissues and can be diagnosed in teeth and jaws of skeletons from archaeological contexts (see PALEOPATHOLOGY and TAPHONOMY). Four dental lesions will be considered here: one developmental lesion (enamel hypoplasia (EH)) and three degenerative lesions (dental caries, antemortem tooth loss (AMTL), and periodontal disease). Because EH forms in childhood during growth of dental tissues it is a developmental disease. This contrasts with dental diseases resulting from infection or decay, such as dental caries, AMTL, and periodontal disease. The prevalence of pathological dental lesions, associations between types of lesions, and the sequence of dental diseases during an individual's life depend on biological and cultural/behavioral factors. These include mode of subsistence, extent of food processing, and frequency of food consumption, factors that often vary by sex or social status. Insights gained from the analysis of EH are followed in this

entry by a focus on dental caries and associated degenerative pathological lesions.

Enamel hypoplasia is a reduction in enamel thickness due to a temporary disruption in the secretion of enamel matrix by ameloblasts (enamel-producing cells). Secretory phase ameloblasts are sensitive to stressors such as undernutrition, febrile disease, infection, and trauma (see INFECTIOUS DISEASE and MALNUTRITION). When enamel matrix is fully mineralized it remains unchanged and unaltered for life with few exceptions: dental wear and cultural modification (etching and inlays, see DENTAL DECORATION). Hence, EH provides an indelible and retrospective record of systemic physiological disruption in an individual's growth and development (see HUMAN GROWTH AND DEVELOPMENT). Due to these attributes, EH has been the focus of intense study to gain insight into group differences in relative health of past populations. EH is expressed as a linear indentation or groove of varying depth and width on the outer enamel surface encircling the tooth crown (Figure 1a,b), hence the term linear enamel hypoplasia (LEH). The ease with which LEH defects are observed contributes to its prominence in bioarchaeology research. Multiple LEHs may occur on a single tooth crown indicating repeated stress episodes during childhood when tooth formation occurred. Because the timing of tooth enamel formation is known, the location of LEH defects on the tooth crown allows an estimate of the individual's age at the time stress occurred, as well as stress duration and severity. Extensive studies of LEH in skeletal samples show that stress is more frequent and repetitive in farmers (versus foragers), slaves and poor-house samples (versus free and independent samples), low-status groups (versus middle and high status), rural (versus urban), and famine survivors (versus pre- or post-famine groups). Evidence of sex differences in frequency and level of stress is less conclusive, even in groups actively practicing son preference and daughter neglect. The biological buffering of female development

may explain this as a mechanism for protecting women's reproductive function. Larsen (2015, 52–57) provides an extended discussion of stress histories in human populations.

Pathological lesions

Three dental diseases—caries, AMTL, and periodontal disease—are often used in bioarchaeology (see BIOARCHAEOLOGY) to reconstruct diet and oral health in past populations (though other scientific methods of dietary inference are used—see DIET AND CARBON ISOTOPES; DIET AND SULFUR ISOTOPES; and FOOD RESIDUE ANALYSIS). The expression and frequency of these lesions in individuals and in past populations are interdependent and impacted by variables including dental wear and irregularities in the outer enamel surface due to EH and crown morphology. For example, two ancient Native American groups—one hunter-gatherer, the other horticultural—had different food processing technologies (wooden mortar and pestle versus sandstone *mano* and *metate*), causing differences in dental wear. The differences in subsistence method, food consumed, and food processing techniques resulted in clear differences in dental caries prevalence. Expanding on this example, the definition, diagnosis, and expression of three pathological dental lesions are documented (see DIFFERENTIAL DIAGNOSIS), then two comparisons are presented: first, an example of how oral diseases interact and exhibit different etiological pathways in foragers and farmers, and second, a summary of biological factors causing sex differences in dental caries and resulting in poorer oral health of women.

Dental caries

Dental caries is a disease process involving progressive, demineralization of dental hard tissues by organic acids derived from bacterial fermentation of dietary carbohydrates, especially refined sugars (Larsen 2015; Lukacs 2012). Diagnosis of dental caries in archaeological samples is different from caries detection in clinical samples. In bioarchaeology, dental caries lesions are routinely diagnosed as focal areas of cavitation in enamel

and dentine (Hillson 2001). In clinical research on living groups, dental caries is a dynamic process of demineralization and remineralization which produces a “white spot” or subsurface demineralization that precedes cavitation. This difference in caries diagnosis makes direct comparison of caries rates between past and present populations problematic. In ancient samples, vigilance is essential in distinguishing postmortem destruction of the tooth crown and root from cavitation due to cariogenesis.

Antemortem tooth loss (AMTL)

Loss of teeth during life is recognized by progressive resorption of the alveolus, a condition that may result from periodontal disease, penetrating caries, severe occlusal wear, or trauma (Lukacs 2012). Regardless of cause, once a tooth is lost, osteoclasts begin the process of resorbing alveolar bone, resulting in the progressive elimination of the alveolus. Alveolar resorption is quite variable but proceeds rapidly in the first years following tooth loss, then more slowly until the alveolus is obliterated. The cause of AMTL cannot be determined from a resorbed alveolus, though potential causes may be identified by observing the presence and patterns of associated dental attributes (degree of tooth wear) and pathological lesions (caries, periodontal disease).

Periodontal disease (periodontitis)

Inflammation and destruction of periodontal tissues anchoring the tooth to the jaw is referred to as periodontal disease. This condition results from the accumulation of bacterial plaque at the gingiva and causes reduction in height of the alveolar crest (Ogden 2008). Periodontal disease is often divided into two general categories: gingivitis and periodontitis. Only periodontitis is recognizable in skeletal specimens, by destruction of the tooth's connective tissue attachment and the loss of alveolar bone (Wasterlain, Cunha, and Hillson 2011). Periodontal disease is multifactorial, but in the absence of plaque it will not occur. Calculus, diet, and oral hygiene influence the onset and progression of periodontal disease. In dry bone it is difficult to distinguish remodeling due to

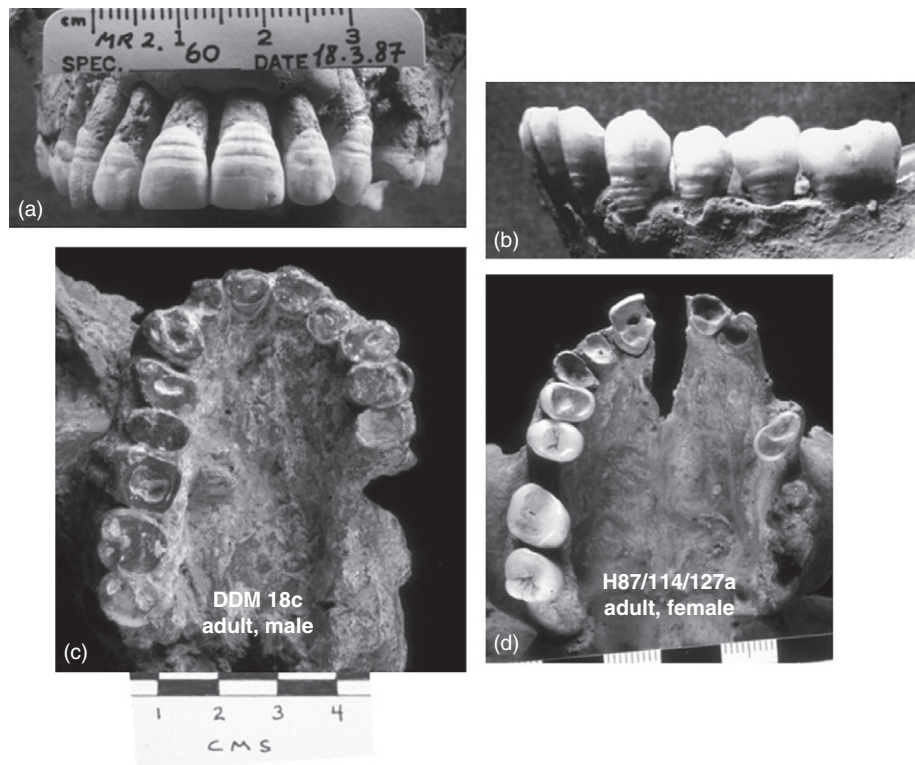


Figure 1 (a and b) Repetitive linear enamel hypoplasia, Chalcolithic Mehrgarh (4500 BCE): (a) MR 2: 60 (adolescent) two prominent LEH in central incisor and canine teeth; (b) MR 2: 34 (adolescent) four independent LEH visible on the lower left canine. Fewer events are visible on the lateral incisor and premolar teeth. (c and d) Pathological dental lesions in specimens with different modes of subsistence: (c) hunter-forager (Damdama) with AMTL of left molar teeth and pulp exposure visible in four teeth (RC, RP3, RM1, LC) due to severe dental wear; (d) farmer (Harappa) with slight dental wear, extensive AMTL (left molar row, P3, C; RM1), and pulp exposure due to penetrating caries in four teeth (RC, RI2, LI1, LI2).

periodontal disease from remodeling due to tooth wear, occlusal force, and continuous eruption.

Subsistence

Subsistence (food acquisition), diet (food ingested), and nutrition (adequacy of diet to support growth and health) are closely related components of a population's success and vitality. Important differences have been consistently observed in the oral health of foragers (or hunter-gatherers) versus farmers (agriculturalists). In this comparison, contrasting patterns of oral health are documented for two South

Asian groups. One is an aceramic, microlithic, seminomadic hunting-foraging group in the Gangetic Plain of north-central India (Damdama, 8800–8600 BCE; Lukacs and Pal 2016). The second is a sedentary, urban, Bronze Age farming group of the Indus Valley Civilization (Harappa, 2550–2030 BCE). Distinctive oral health differences between these two groups are exhibited in degree of tooth wear, caries prevalence, periodontal disease, and the cause of AMTL. In foragers the prime cause of AMTL is severe occlusal wear, while in farmers severe dental caries is the main cause. These differences are illustrated in the maxillary dental arcades of a Mesolithic forager from Damdama (Figure 1c) and a Bronze Age farmer from Harappa (Figure 1d). Note

differences in size of the maxilla, size of the teeth, severe degree of wear, pulp exposure, and AMTL in the Mesolithic forager, and numerous carious teeth, caries-induced pulp exposure, slight degree of wear, and AMTL in the Bronze Age farmer.

Sex differences

Sex differences in oral health are a common finding in the oral epidemiology of living populations and in the dental pathology profiles of past populations. Anthropologists typically explain poorer oral health in women (e.g., higher prevalence of AMTL and caries than men) as the result of sex differences in diet and behavior (Lukacs 2017). Since women prepare and cook food in most societies, they are closer to food supplies and have greater opportunity to snack and test foods during the cooking process than men. In addition to diet and behavior, physiological and hormonal differences between the sexes have been shown to influence susceptibility to caries and other dental diseases. Literature reviews reveal a pervasive and ubiquitous tendency for females to have higher rates of dental caries and AMTL than men—a trend seen in different societies, geoclimatic zones, and time periods.

Global data from epidemiological surveys of living groups show that during childhood males have significantly higher caries prevalence than females, or there is no intersex difference (Lukacs 2017). Yet among young adults, females have higher caries prevalence than males. This transition in oral health is likely due to the onset of puberty and menstrual cycling in women. These hormonal changes alter oral ecology in ways that promote cariogenesis. This shift is accompanied by accentuation of the sex bias toward poorer oral health (higher caries rates) during a female's reproductive years. Menstrual cycling and pregnancy cause biochemical changes that reduce saliva flow and alter saliva biochemistry, making the oral environment less antimicrobial and less able to buffer acid challenges that accompany ingestion of food. The increase in caries with agriculture is typically attributed to the change in subsistence and diet. However, the increase in fertility with the adoption of agriculture may be as important in explaining the decline in women's oral health as the difference in diet.

These ideas represent a significant change in the anthropological perspective on sex differences of oral health because greater recognition is now given to women's sex hormones and the cumulative effect of women's reproductive biology (menses and pregnancy) throughout the life course. The shift in perspective on the complexity of factors impacting women's oral health is clearly evident (see Larsen 1997, 72–76; 2015, 73–77). The study of oral health in past populations enhances our understanding of the intricate interaction of biology and behavior in human prehistory.

SEE ALSO: Bioarchaeology; Dental Decoration; Dental Development; Diet and Nitrogen Isotopes; Diet and Trace Elements

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Osteology

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At its most basic, osteology is the study of bone. More specifically it is the scientific study of the structure and function of the skeleton. The analysis of the skeleton can be employed in a variety of contexts and disciplines, from human osteology, often examined by anthropologists and human anatomists, to faunal bone studied by zoologists, zooarchaeologists (see ZOOARCHAEOLOGY), and paleontologists. The study of skeletal material is fundamental to these disciplines because of the information that can be gleaned from it and its durability. In archaeological and paleontological contexts, the skeleton is often the only record left of the once-living animal. It can provide information on the structure of the body that can then be informative on its function. Skeletal structures are not static during life; they are instead molded by the activities of the living creature. In this way, the skeleton can help the osteologist reconstruct what the living creature was like: its diet, its health, how it moved around the landscape, its biological sex, age-at-death, and so on. Skeletal structures also reflect the evolutionary history of the animal and can be used to determine evolutionary relationships between different taxa.

Human osteology is the study of the human skeleton and is fundamental to much of the work of biological anthropologists. It is the cornerstone of human skeletal biology and paleoanthropology. Two of the major areas in human skeletal biology are bioarchaeology (see BIOARCHAEOLOGY) and forensic anthropology. Osteology is critical to these areas as it helps these practitioners determine as much as possible about the recovered human skeletal material including:

- age-at-death (see ESTIMATING ADULT AGE: AURICULAR SURFACE MORPHOLOGY; ESTIMATING ADULT AGE: PUBIC MORPHOLOGY;

ESTIMATING ADULT AGE: TRANSITION ANALYSIS; ESTIMATING SUBADULT AGE: DENTAL DEVELOPMENT AND ERUPTION; ESTIMATING SUBADULT AGE: DIAPHYSEAL LENGTH; and ESTIMATING SUBADULT AGE: EPIPHYSEAL UNION)

- sex (see ESTIMATING SKELETAL SEX: CRANIAL AND PELVIC MORPHOLOGY and ESTIMATING SKELETAL SEX: METRICS)
- ancestry (see BIOLOGICAL DISTANCE)
- stature (see STATURE ESTIMATION)
- health (see ORAL HEALTH and PALEOPATHOLOGY)
- diet (see HUMAN SKELETAL GEOCHEMISTRY and MALNUTRITION)
- activity and trauma (see MUSCULOSKELETAL STRESS MARKERS and TRAUMA)
- perimortem events.

This information may help identify the individual, or what happened to them (forensic anthropology), or be aggregated with similar information from other skeletonized individuals to gain a population-level understanding about an ancient society (bioarchaeology). In paleoanthropological contexts, osteology is used to determine if the recovered fossilized bone is from a hominin, and if so what that bone might suggest about which of the hominin taxa it belongs to. Paleoanthropologists can then use their analysis of the skeleton to try to reconstruct, as much as possible, the sex, age-at-death, and stature of the fossilized individual. Aspects of daily life, such as diet and health, may also be revealed through osteological analysis of the fossil material. This information may help give a greater understanding about the extinct species.

Human osteological research has historically dominated biological anthropology, a trend that continues to this day. From its onset, osteological research has been highly descriptive. While descriptive research still dominates much of the reported osteological research, there has been a significant increase in analytical research, with an emphasis on hypothesis testing (Hens and Godde 2008). The earliest research in osteology

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was focused on understanding human variation to aid in defining the race concept in humans (Armélagos, Carlson, and Van Gerven 1982). While understanding the nature of variation is still of significant importance in the field, much of the current research in this area is instead focused on methods to accurately assess basic demographic information such as age-at-death, sex, and ancestry for forensic and archaeological applications (see PALEODEMOGRAPHY) instead of for hierarchical racial classifications (Hens and Godde 2008; Stojanowski and Buikstra 2005).

Osteological analysis is often done at the macroscopic level. This involves visual inspection of the bone and comparisons with known element collections, especially for highly fragmented materials. Measurements can be taken to help in estimations of age, sex, ancestry, and stature (see DENTAL METRICS). In fact, among the earliest research in osteology was the metric analysis of human morphological variation to understand the origin and extent of human racial variation. Microscopic or histological examination of bone can be used in assessments of age-at-death and health. Bone chemistry and DNA analysis are also increasingly performed to aid in the identification of the individual (see DNA: MITOCHONDRIAL; DNA: NEXT GENERATION SEQUENCING; GENETICS: ANCIENT; and GENOMICS: ANCIENT), as well as in reconstructions of diet and migration in the past (see DIET AND CARBON ISOTOPES; DIET AND NITROGEN ISOTOPES; DIET AND SULFUR ISOTOPES; DIET AND TRACE ELEMENTS; MOBILITY AND LEAD ISOTOPES; MOBILITY AND OXYGEN ISOTOPES; and MOBILITY AND STRONTIUM ISOTOPES).

Faunal bone may be studied by zooarchaeologists, zoologists, and paleontologists. For anthropological questions, much of the relevance of faunal analysis relates back to questions about ourselves, in particular what the fauna might tell us about the environment and activities of the humans that lived contemporaneously. The analysis of faunal bone can determine the taxon and element of the bone. This might

give information from the kinds of species that shared the landscape with a fossil hominin to what was on the menu for an ancient group (see ZOOARCHAEOLOGY AND HUMAN DIET RECONSTRUCTION) or how that group moved across the landscape (see ZOOARCHAEOLOGY AND HUMAN TRADE AND MIGRATION).

SEE ALSO: Degenerative Joint Disease; Discrete Traits; Human Growth and Development; Human Skeletal Data Quantification; Infectious Disease

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Paleodemography

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Demography is the study of population over time and space. Demographers describe, statistically, the size, density, and distribution of populations across space, and rates of fertility, mortality, migration, and population growth (or decline) across time. Paleodemography attempts to provide similar description of ancient populations using data from human skeletons. An important characteristic of paleodemography has been its focus on cultural, ecological, and behavioral processes and their impact on ancient demographic patterns and community health. Though there are many examples of ancient health studies, understanding community health has proven an elusive goal. Reconstructing the demography of ancient populations is essential to the testing of evolutionary theories of human behavior, resource intensification, cultural evolution, and ecological degradation.

Paleodemography grew in the 1960s and 1970s as evolutionary and ecological approaches to human behavior were at the forefront of anthropological archaeology. J. Lawrence Angel outlined the goals and promise of paleodemography in his (1969) article “The Bases of Paleodemography” as follows: to reconstruct the “population picture” of an ancient settlement including age composition, age-specific mortality, adult longevity, and sex ratio, and “if possible” fertility and rates of natural increase. During the 1960s and 1970s, paleodemography focused on relationships between human health and demography and culture change, especially the consequences of the adoption of agriculture as exemplified by syntheses of culture change and mortality (e.g., Acsádi and Nemeskeri 1970). These early studies focused on changes in human mortality through the construction of life tables from excavated skeletal collections,

and on the use of skeletal lesion frequencies as indicators of prehistoric health conditions. Paleodemographic life tables depend on two critical assumptions: first, that the population that produced the skeletal sample was stable, that its fertility and mortality rates were constant over an extended (<100 years) period; and second, that the population was stationary, neither growing nor declining. A major conclusion of these early studies, based on declines in the mean age at death and increases in lesion frequency, was that the shift from foraging to farming brought significant negative consequences for human health.

Paleodemography began a period of thorough self-evaluation and self-critique in the 1980s. Three critical analyses dragged paleodemography out of its childhood. First, Bocquet-Appel and Masset's (1982) “Farewell to Paleodemography” identified the “reference sample” problem as a critical source of bias in age at death estimates. Second, Sattenspiel and Harpending (1983) demonstrated that fertility and population growth, rather than mortality, were the primary determinants of the mean age at death (MAD) and the overall age distribution of death in a given population. MAD had been broadly used as a proxy for life expectancy at birth. This recognition had profound implications for previous studies, which had, based on life tables, identified declines in “life expectancy” following the adoption of agriculture as evidence that agriculture had been detrimental to human health. Following Sattenspiel and Harpending, declines in mean age at death are primarily evidence of increased fertility and population growth. Third, Wood and colleagues (1992) introduced the concepts of heterogeneous frailty, hidden heterogeneity, and selective mortality to paleodemography. The “osteological paradox” called into question basic assumptions about the relationship between lesion frequencies and ancient health conditions. This tradition of disciplinary self-critique has led

to ongoing efforts to remove bias from skeletal aging techniques (Hoppa and Vaupel 2002), and to better understand the relationship between cemetery samples and living populations (e.g., DeWitte and Wood 2008; Paine 2000).

The data of paleodemography are archaeologically recovered human skeletons. Paleodemography employs morphological markers associated with age and sex and skeletal lesions associated with malnutrition or pathology to reconstruct basic demographic rates and patterns. As the human body develops and matures, it goes through a series of predictable morphological changes associated with growth. These include the formation and eruption of teeth and the gradual closure of skeletal epiphyses. The adult ages are also linked to morphological changes in the skeleton. These include changes in the major joints of the pelvis (the pubic symphysis and iliac auricular surface) and the sutures of the cranium. Because developmental changes in skeletal morphology are fairly consistent, where the morphological changes associated with estimation of adult age are heavily influenced by individual health conditions, age estimates become less precise and interobserver differences in age estimates increase as actual age increases.

Commonly used sex markers in the skeleton do not appear until individuals reach full reproductive age. Therefore, it has been generally considered to be impossible to estimate sex for subadults, though osteologists continue to seek new markers, including features of subadult mandibles and eye orbits. Several experimental studies have attempted to determine the sex of subadults using DNA recovered from excavated skeletons. These methods have focused on the amelogenin gene, which varies in size between the X and Y chromosomes, and on genes located on one of the sex chromosomes, usually the Y. Because ancient DNA recovery is both expensive and destructive, these techniques are not yet practical on a large scale.

Preservation may have strong effects on age and sex estimates from excavated skeletal series, including methods that employ ancient DNA. Preservation conditions vary from site to site and even between adjacent graves. Some morphological features are more commonly preserved than others; within the same skeletal series,

morphological markers available to estimate age and sex may vary between individual skeletons.

Reference sample bias

Bocquet-Appel and Masset (1982) were the first to draw attention to statistical biases resulting from the use of reference samples. They showed the statistical tendency of studied series to be drawn toward the reference samples. Reference samples, like the Hamann-Todd collection, are collections of skeletons associated with a documented age at death. They are used to describe morphological changes in the skeleton that come with age. Unfortunately, these collections tend to have unique age and sex distributions reflecting their source populations. For example, the Hamann-Todd collection, housed at the Cleveland Museum of Natural History, the United States, is made up of unclaimed individuals from Cleveland area hospitals and the Cuyahoga County morgue. The collection skews toward men, especially adult men from precarious economic situations. This type of bias is typical of known-age collections. The range of variation in morphological change correlated with age is captured more fully in overrepresented age and sex subgroups and less fully in age and sex subgroups that are not so well represented. Any morphological aging method that is based on observations of a reference sample will cause age estimates to be drawn toward those overrepresented categories (Bocquet-Appel and Masset 1982; Hoppa and Vaupel 2002). Several authors (e.g., Hoppa and Vaupel 2002) have developed methods to produce age estimates which are not affected by reference sample bias. These methods apply an informative prior distribution (an estimate of the likely age at death distribution for the study population) and Bayes' theorem to unknown skeletal samples. Though mathematically complicated, these methods have proven successful. Today, paleodemographers have the choice to employ unbiased methods, including Boldsen and colleagues' (2002) transition analysis (see ESTIMATING ADULT AGE: TRANSITION ANALYSIS), and increasingly are doing so.

Heterogeneous frailty/hidden heterogeneity

Every individual in a population has a unique ability to resist death, referred to as their frailty. This heterogeneity of frailty is based on many factors including age, sex, genetics, local environmental conditions, socioeconomic status, and diet. Over time, there has been an important shift in emphasis away from viewing heterogeneity as a hindrance to research, toward making it a focus of paleodemographic study. This has been particularly important in studies of complex societies where archaeology can supply evidence of heterogeneity in socioeconomic conditions, for example. In the future, presently hidden heterogeneity like childhood nutritional patterns may become the focus of frailty studies as isotope and elemental studies of tooth enamel become practical and affordable.

Selective mortality

In his pioneering work, Angel (1969) pointed out that lesion frequencies in skeletal series are not direct reflections of frequencies in a living population. They represent only the subset of individuals who died at any given age. Mortality is not random; it is selective. On some levels, those who are most frail will have higher mortality than those who are less frail. Therefore, skeletons, regardless of age, represent the frailest members of a population. For example, the 20-year-old in a skeletal series is not representative of 20-year-olds from the living population, most of whom would be expected to live many more years; the former represents the rare 20-year-old who died. This has important implications for studies that attempt to assess ancient community health using lesion frequencies.

Since the 1980s, many studies have attempted to examine, explicitly, the links between ancient health conditions and effects and their outcomes in skeletal series. Two approaches have characterized these attempts. The first is the use of hazards analysis to explore the relationship between skeletal markers (e.g., height, the presence of lesions), heterogeneous frailty, and mortality. DeWitte and Wood's hazards analyses of Black Death cemeteries in England (DeWitte and Wood 2008) are an excellent example of such

work. They explore selectivity in plague mortality using height and nonspecific lesions as proxies for frailty. The second is the use of population models to simulate the effect of demographic events on skeletal age distributions. Paine's (2000) examinations of the outcomes of epidemic events are an example of modeling population processes to understand their impacts of skeletal age distributions. After three decades of intense self-critique and theoretical and methodological advancement, paleodemography has a better overall understanding of its data, their limitations and potential, than most areas of ancient studies.

SEE ALSO: Bioarchaeology; Dental Development; Estimating Adult Age: Auricular Surface Morphology; Estimating Adult Age: Pubic Morphology; Estimating Adult Age: Transition Analysis; Estimating Subadult Age: Diaphyseal Length; Estimating Subadult Age: Epiphyseal Union; Life Table Analysis; Osteology; Paleodemography and Hazards Analysis; Paleopathology

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Paleodemography and Hazards Analysis

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Hazards analysis is a potentially powerful way to derive paleodemographic information (see PALEODEMOGRAPHY) from skeletal samples, which are often relatively small and plagued by problems of missing data resulting from various selection processes such as selective mortality, preservation bias, systematic variation in burial practices or locations, and incomplete excavation (Milner, Wood, and Boldsen 2008). Hazards analysis provides an alternative approach to paleodemographic life table estimation (see LIFE TABLE ANALYSIS) (Konigsberg and Frankenberg 2013; Wood et al. 2002). Hazard models specify the time until a certain event occurs, such as death in the case of skeletal samples. Hazards analysis often involves using skeletal data to estimate the parameters of a mortality function, survivorship function, or age-at-death distribution (all of which are related equations). Models with few parameters can be applied to small samples, and they smooth the random variation in mortality data that is an artifact of small samples, without imposing any particular age pattern on the data. Hazard models also accommodate missing data, which is important given the incomplete nature of many skeletal samples and when, as is often the case, bioarchaeologists use age estimation methods that do not provide good estimates for older adults ages (i.e., many methods yield broad terminal age-intervals; however, see ESTIMATING ADULT AGE: TRANSITION ANALYSIS).

Examples of useful parametric models are the Gompertz, Gompertz–Makeham, and Siler models (Wood et al. 2002). The Gompertz mortality function describes the senescent pattern that is typical of human populations: Mortality is relatively low at early adult ages and then increases rapidly at older ages. The mortality function has two parameters: One represents the

overall level of mortality due to aging, and the other represents the rate at which the force of mortality increases with advancing age. It is based on a model of aging that assumes physiological capacity declines with age as a negative exponential and that the risk of death is proportional to the amount of physiological capacity remaining to an individual (Gage 1989). This assumes a relatively simple relationship between physiological capacity and mortality, which might not always be true. More complex and thus perhaps more realistic models would require additional parameters, but increasing the number of model parameters increases the sample sizes required. Small samples typically require paleodemographers to choose models with few parameters that are therefore estimable, rather than models with many parameters that more closely reflect reality but require inaccessibly large samples.

The Gompertz–Makeham model includes a hazard (the Makeham component) that is constant across all ages; it is associated with exogenous causes, such as accidental deaths, that are independent of age or the physiological state of an individual. The Gompertz–Makeham model incorporates the idea of competing hazards or causes of death. There are multiple possible causes of death and they are independent of each other, so individuals who avoid one cause of death are subject to the remaining causes of death in the same manner as everyone else. Surviving the causes of death associated with the Makeham component has no effect on one's risk of death from causes associated with the Gompertz component. It can be difficult to estimate the Makeham component with small, incomplete samples (Herrmann and Konigsberg 2002).

The Siler model adds an immature component (a negative Gompertz function) to the Gompertz–Makeham model to reflect the common pattern of relatively high mortality at birth followed by a rapid decline during infancy and childhood. This component has two parameters: One represents the initial force of mortality associated with infant and childhood causes, and the other represents the rate at which

this declines with increasing age. A possible biological interpretation of this immature component is that mortality is proportional to the likelihood of infection and inversely proportional to the level of immune competence, so as children get older, their immune competence improves and the likelihood of infection, and death thereof, declines. The three components of the Siler model combined approximate the roughly U-shaped curve of mortality observed in human populations.

Hazard models can be fit to age-specific survivorship rates, the force of mortality, or the age structure (the probability density function (PDF) of ages at death) (Gage 1988). It is best to fit the survivorship function when the data are likely to be accurate, as this does not require assumptions about the stability or stationarity of the population. However, if the data are defective (as is typical of paleodemographic data), it is better to fit the force of mortality or age structure.

In addition to these fully parametric models, paleodemographers have applied semiparametric and nonparametric approaches to assessing survival and mortality. For example, the Cox proportional hazards model is a semiparametric model that allows for the estimation of the risk of death and of the effects of variables (e.g., sex, urban versus rural, high versus low status) on that risk. It does not, however, require the specification of a baseline hazard of mortality, and so parameters for a hazard function are not estimated. Survivorship and variation thereof within or between populations can also be assessed nonparametrically using Kaplan–Meier survival analysis. These approaches can be applied to

smaller samples than those required for fully parametric analyses.

SEE ALSO: Bioarchaeology; Estimating Adult Age at Death: Cranial Suture Closure; Estimating Adult Age: Auricular Surface Morphology; Estimating Adult Age: Pubic Morphology

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Paleopathology

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Paleopathology is viewed as an interdisciplinary and multidimensional discipline that focuses on the study of health conditions of past individuals and populations, aims to trace the origin and evolution of diseases, and reconstructs individuals' and populations' health profiles (Ortner 2003). Its goals are holistic and imply biocultural interpretations of disease. Therefore, to allow an accurate understanding of the past, and assess the impact diseases would have had, contextualizing all information used in paleopathological analysis is in order. Thus, it is not sufficient to understand signs and symptoms of disease in current living populations—used as proxies—to think about the past. In paleopathological studies, cultural and social interpretation of signs and symptoms of a disease need to be contextualized. This is relevant since a cultural filter may impact the manner by which the concept of “disease”, or being “ill,” is lived by the affected individual and perceived by the population at large.

This growing sensitivity to context in paleopathological cases reflects the changing body of scholars involved and trained in the discipline. Earlier scholars had mostly a medical training, with studies focusing on individual skeletons or mummies, such as case studies and osteobiographies. Scholars from the second half of the twentieth century onwards have a more diversified academic background, with an emphasis on social sciences and humanities such as anthropology and archaeology. Nevertheless, paleopathology continues to be associated with many diverse academic departments (e.g., anthropology, archaeology, anatomy, pathology, radiology, and any other fields related with medical sciences, including forensics), and each scholar will inevitably associate paleopathology with his/her theoretical and academic background. In this text, the term paleopathology—and

paleopathologists—will be used in reference to those that study evidence of disease in the past via analysis of human bone, tissues, and teeth.

Paleopathology has progressed scientifically since its early onset. Charlotte Roberts and Jane Buikstra's edited volume *The Global History of Paleopathology: Pioneers and Prospects* (2012) offers an overview of the history of paleopathology, outlining the practice of paleopathology in various regions of the globe and allowing for a first-hand expression of the many scholars who are actively engaged in the discipline worldwide.

Paleopathology uses human skeletons and/or commingled bones and teeth as primary sources of data. Skeletal remains contain a great amount of information regarding an individual's ancestry, behavior, and disease. Evidence of disease in human remains is as old as human evolutionary history itself. The diagnosis that Lucy, a 3.18-million-year-old *Australopithecus afarensis*, had suffered a traumatic injury is illustrative of the case. Most of the human remains studied in paleopathology are far more recent than Lucy's 3 million years of age. Nevertheless, the chronology ranges from the Paleolithic (10,500–8000 BCE) to contemporary human remains. An example of this impressive overarching chronology is the project *A History of Health in Europe over the Past 10,000 Years* (<https://www.dur.ac.uk/research/directory/view/?mode=project&id=402>).

The goals of paleopathology are varied, reflecting the discipline's interdisciplinary and multidimensional scope, ranging from the simple macroscopic observation of bone and teeth changes aiming to diagnose a disease in an individual, to the reconstruction of long-term trends and patterns of disease in populations: all while exploring disease association with biological and social inequalities, and how these may relate to sex, age, work, and ultimately disease itself. With the development of ancient DNA analysis (see GENETICS: ANCIENT), and other biochemical and biomolecular techniques, paleopathology expanded its aims to the understanding of disease at a microscopic and evolutionary level. New

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insights into population migration (see MOBILITY AND LEAD ISOTOPES) and how it may relate to population genetics, and both of the previous with pathogens, have favored exploring the coevolution of humans and pathogenic organisms.

In addition to skeletons, some paleopathological cases consist of mummies (e.g., Egypt), or bodies in peat bogs (e.g., bog bodies in Denmark), as certain environments and/or body manipulation techniques preserve more than bones and teeth. These remains offer complementary information to that observed in bones, since soft tissue can be analyzed. Preserved feces (coprolites) (see COPROLITES) have also yielded important information on agents associated with diseases. Some studies have been successful in recovering and identifying preserved eggs of parasites, such as roundworm and whipworm (see PARASITOLOGY). Additionally, secondary sources of information, such as paintings, religious statuary, pottery, burial goods, and written documents are important in paleopathology (Buikstra and Beck 2006; Grauer 2012; Ortner 2003).

The rationale behind paleopathological analysis is simple: It assumes that abnormal bone changes have a pathological nature, if not caused by deterioration after death and burial. Tissue deterioration will have a negative impact in paleopathology as it may cause a difficulty for, and even prevent, any type of analysis. Therefore, before addressing pathological bone changes, postmortem bone changes need to be evaluated when undertaking a paleopathological study. Taphonomy (see TAPHONOMY) is the study of such postmortem changes, and includes multiple factors that act upon a body after its death and until it has been environmentally recycled. The reference to taphonomic changes includes all postmortem abnormal modifications observed in bone and teeth that are the result of either the immediate burial environment and/or problems during or after excavation. These postmortem changes are also known as pseudopathological, since it is often difficult to macroscopically differentiate between both pathological and taphonomic changes, particularly when remains are poorly preserved or modified. Bone changes resulting from burial practices such as cremation exemplify the latter. Bone and teeth exposure to heat will fragment and modify their shape and form, and color, challenging an accurate

assessment of any changes of pathological nature. However, this burial practice offers insights into a community's social and cultural behavior.

Paleopathological analysis starts with an assessment of the remains biological profile. This includes the assessment of sex and age at death (see ESTIMATING ADULT AGE: AURICULAR SURFACE MORPHOLOGY; ESTIMATING ADULT AGE: PUBIC MORPHOLOGY; ESTIMATING ADULT AGE: TRANSITION ANALYSIS; ESTIMATING SKELETAL SEX: CRANIAL AND PELVIC MORPHOLOGY; ESTIMATING SKELETAL SEX: METRICS; ESTIMATING SUBADULT AGE: DIAPHYSEAL LENGTH; and ESTIMATING SUBADULT AGE: EPIPHYSEAL UNION). When addressing commingled human remains, that is, disarticulated remains, these two biological parameters may be extremely difficult to infer, although not impossible. The skeleton is also assessed for anatomical variation. This includes bone measurements and assessments of shape and form, aiming to calculate stature and morphological parameters such as robusticity. In addition, nonpathological variations are assessed, including discrete traits (see DISCRETE TRAITS), also known as epigenetic traits, which are considered nonpathological but expressions of an individual's uniqueness. This recording is the basis of paleopathological studies: it is very important to understand the wide range of anatomical variation, as well as taphonomic or disease-related changes. After establishing the biological profile, all bone changes are recorded. Standardized recording protocols are mandatory so that reliable and objective data can be collected, allowing future comparisons between populations and ensuring the accurate characterization of bone change and diagnostic criteria of pathologies (Buikstra and Ubelaker 1994). Ideally, recording bone changes should use unambiguous terminology, precise identifications of the location and distribution of bone changes, and descriptive summaries of the morphology of the change.

Detailed description of the location and type of changes is essential in paleopathology, as bone tends to react to stress in very similar manners, exhibiting either remodeling or destruction of bone tissue, or both. Thus, often the location, distribution, and pattern of changes are essential to perform a diagnosis. For example, infectious diseases such as tuberculosis preferentially affect the ribs and spine, with preference for the thoracic

vertebrae, while changes in the bones of the face, hands, and feet are more likely to be related to leprosy (Ortner 2003). Fortunately, even when assessing damaged and incomplete skeletons, pathological diagnoses, as well as the exercise of differential diagnosis (see DIFFERENTIAL DIAGNOSIS), are still possible as certain diseases have pathognomonic traits, that is, disease-specific bone changes. For example, eburnation (polishing) of articular surfaces is pathognomonic of osteoarthritis, and a flowing ossification along the anterolateral body of thoracic vertebrae is a criterion used to positively discriminate diffuse idiopathic skeletal hyperostosis (DISH), also known in the medical literature as Forestier's disease. In the absence of pathognomonic traits one may still allocate particular bone changes to specific disease categories such as trauma (see TRAUMA), development or congenital diseases (see CONGENITAL CONDITIONS), metabolic (see METABOLIC DISEASE) and endocrine diseases, tumors or neoplastic conditions (see CANCER), infectious diseases (see INFECTIOUS DISEASE), joint diseases (see DEGENERATIVE JOINT DISEASE), oral diseases (see ORAL HEALTH), nonspecific infectious diseases, and others that tend to fall into a category of miscellaneous conditions (Ortner 2003; Grauer 2012).

Paleopathology addresses both individual cases (e.g., osteobiographies) and population studies that are essentially hypothesis driven. In both, the methods of recording changes are the same, and involve recording all that is non-normal bone change. However, in population studies, the recording of non-normal changes may target specific bone changes and/or anatomical locations aiming to explore and study a specific pathological condition. For example, to assess degenerative joint diseases (DJD), researchers focus on the articular surfaces and record the known DJD—porosity, eburnation, and marginal and surface osteophytes (Buikstra and Ubelaker 1994, 115). The end result is a disease-specific population study. Exclusion of cases that may bias the presence of DJD (or pathology under study) is mandatory. Also, it is extremely important to consider the context. When studying a population with a high frequency of DJD, researchers need to consider confounding factors that may bias the results, such as age, sex, living conditions, occupation, and activity patterns.

Paleopathological bone changes are primarily observed with the naked eye, or in some cases with the aid of a binocular microscope. However, with growing awareness of the complexity of bone tissues' response to stress, and the relevance of taphonomy, complementary methods of analysis have been increasingly used, including imaging techniques such as radiography, computerized tomography (see COMPUTED TOMOGRAPHY), and 3D laser scanning (see LASER SCANNING). These allow for a nondestructive approach to studying bone changes. Unfortunately these techniques are not accessible to all paleopathologists. Histological analysis of bone tissues (paleohistology) and ancient DNA analysis (paleogenetics) are also used. Paleogenetics has permitted the positive identification of pathogens responsible for a series of diseases such as tuberculosis, leprosy, and syphilis, opening new research avenues and hypothesis-driven studies in paleopathology. The same applies to paleohistology, which uses histological techniques on bones recovered from archaeological sites. Paleohistology deepens the understanding of bone tissue morphology and shows stages of cellular activity, such as excessive tissue mineralization and signs of abnormal bone reabsorption associated with past diseases. Paleohistology is also highly important in cases aiming to differentiate between antemortem and postmortem bone changes to facilitate differential diagnosis. However, despite the magnificent insights these techniques offer, they require both the destruction of bone and tooth samples, and resources and facilities that are not available to all paleopathologists.

Paleopathology has come a long way from its onset; however, limitations still exist. The accuracy of diagnoses obtained from skeletal evidence and the subsequent interpretation and use to reconstruct the health and behavior of past populations are recurring concerns (Wood et al. 1992). The fact is that many diseases do not leave evidence on the skeleton. Only a small percentage will leave such evidence, depending on a person's (i.e., organism and immune system) capacity to survive stress. Observing disease-related bone changes in skeletons means that the person coped with the condition, but does not necessarily inform about cause of death. Alternatively, it has been acknowledged that the absence of disease-related bone changes does

not equate absence of disease: A person may have had a disease that left no evidence on their bones. Furthermore, poor preservation and/or absence of remains prevents detailed recording of changes, and accurate frequency estimations and methods continue to be subjective as scholars adapt recording protocols to accommodate research questions and fragmentation of the remains. Moreover, paleopathology continues to rely heavily on gross macroscopic observation, contrasting with the few diseases that are credited to leave pathognomonic traits on bones. Paleopathology will continue its development as new techniques and approaches to bone changes are explored and improved.

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Parasitology

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Introduction

Archaeoparasitology is the science that focuses on the relationships between parasite biology, human behavior, and environment that defined past infection patterns. It depends on archaeological information regarding subsistence, medicines, demographics, sanitation, environment, trade, and many other lines of archaeological investigation. It also depends on the understanding of complex parasite life cycles and principles of parasite ecology. In multisite analyses, archaeoparasitology defines various correlations of parasitism associated with the development of complex societies and changes in subsistence. It sheds light on the health impact of urbanization and empire expansion. When tightly applied to a single burial or mummy, archaeoparasitology shows how habits promote infections and disease on an individual basis (Reinhard and Araújo 2016). Latrines, coprolites, and mummies are sources of direct diagnoses. Especially in the Americas, coprolites and mummies provide epidemiological data sources.

Archaeoparasitology has entered a new age of population studies using a spectrum of analytical methods. Molecular biology (aDNA analysis), immunological tests (enzyme-linked immunosorbent assay (ELISA)), scalp examination for lice, and microscopic analysis of sediments are methods for identifying parasites. In addition, gross pathology exhibited in human remains can be used to infer parasitism.

An axiom in parasitology is that a minority of hosts carries the majority of parasites. This is known as the negative binomial distribution. Several studies of both ectoparasites and endoparasites showed that the negative binomial is evident in archaeological series (Camacho et al. 2018). This is of crucial importance

because archaeoparasitology has equivalent epidemiological strength as modern surveys of living populations. Thus, archaeology can show infection patterns of past lifestyles, separated from the modern world by wholly different behavioral adaptations.

Archaeoparasitology entered a new period of diversifying concepts because the field of parasitology has generated a wealth of theoretical perspectives. Many of these can be used to generate hypotheses testable with archaeological data. Some of these, such as the application of the nidus concept, formed the underpinning for the new approach to understanding ancient infection risks. This emerging area is called pathoecology (Reinhard and Araújo 2014, 2016).

Pathoecology is an approach to ancient health assessment that is based on a reconstruction of infection from a variety of parasites evident in a population. For the infection component of pathoecology, the nidus concept of Pavlovsky is useful (Slepchenko and Reinhard 2018). Pavlovsky was a parasitologist who developed the model of any given parasite infection being dependent on the overlap of parasite and host in a geographical space that favors transmission. The nidus is this space. From the archaeoparasitological perspective, this space can be as finite as a room enclosing dog- and human-susceptible hosts that is infested with infected kissing bugs. Within this nidus, the nocturnal kissing bugs are the vector for the parasite *Trypanosoma cruzi* which can cause Chagas disease. In archaeological populations, several parasites are often found at the same site. Because the life cycles of the parasites are known, the overlapping nidi of several parasites can be deduced. Therefore, the nidi and risk behaviors of the populations can be inferred and compared (Reinhard and Araújo 2014, 2016).

When pathoecology is applied on a continental scale, larger comparisons of lifestyle can be made. Fecal-borne parasites were remarkably well controlled in the prehistoric Americas. In contrast, such parasites were ubiquitous in premodern Europe, west of central Russia. Fecal-borne parasites are evidenced by the durable eggs of *Ascaris*

lumbricoides and *Trichuris trichiura*. In Europe, the emergence of ubiquitous filth parasites was associated with population increase at the onset of agriculture. In contrast, filth parasites were rare in the Americas. The behaviors that defined these patterns were addressed by Reinhard and Pucu (2014). For Europe, behaviors that promoted infection included uncontrolled excrement disposal, use of feces as fertilizer, poor personal hygiene, and crowding. Also, the humoral concept, the basis of European medicine, did not recognize the germ theory. Evidence from the Americas suggests that a number of behaviors reduce exposure to feces. These included less crowded conditions, antihelminthic therapies, the establishment of sanitation, the perception of infection causality, agricultural practices that limited pathogen transmission, and the role of diet in the spontaneous clearance of worm infections (Reinhard and Pucu 2014). Therefore, from finite spaces in archaeological sites to large-scale comparisons, the nidus concept and pathoecology are very useful in understanding different trajectories of parasite–human associations.

The parasitological analysis of latrine features can provide the best evidence of parasite emergence and control related to sanitation. Trigg and colleagues (2017) synthesized data accumulated from New England historic sites by several researchers between 1986 and 2007. The data included analysis of 114 latrines from seven cities. The earliest samples date to 1650 and the latest to 1900. Socioeconomic information was overlaid on the archaeoparasitological data. Using this extensive dataset, the authors defined biological and cultural variables that shaped the pathoecology of developing cities. Control of fecal-transmitted parasites was gradually achieved, beginning with *T. trichiura* and eventually with *A. lumbricoides* by the end of the nineteenth century. Transmission and control were defined by changing microenvironments associated with urbanization, development of sanitation, and variable use of urban spaces. Poorer households were more susceptible to infection due to use of feces-contaminated yards for gardening. Also, the poor had a delayed access to sanitation. This study reflects the maturation of archaeoparasitology among historic archaeologists which is based on analysis of large data sources in cultural contexts.

Analysis of the distribution and genetic composition of parasites over long time periods and across large geographic ranges provides insight into evolution of parasites after host switching events. Reinhard and Araújo (2014) review the data for *T. cruzi*. For the last decades of the twentieth century, the conventional wisdom was that *T. cruzi* emerged as a human parasite in the Andes after sedentism developed and animal domestication was innovated. Dogs and guinea pigs are alternative hosts for *T. cruzi*. It was believed that once dogs, humans, and guinea pigs began to live in kissing-bug-infested domiciles, infection became common in humans. This process was called domiciliation. By 2003, evidence of infection predating animal domestication was discovered, as was evidence of *T. cruzi* well outside of the Andean geographic range. The application of molecular biology to large series of mummies revealed a different picture. There was a host switch to humans on the part of *T. cruzi* some 9,000 years ago. Later, molecular biologists were able to test for the six variants of *T. cruzi* DNA. The latter study was enlightening. The oldest infections were with wild strains of *T. cruzi* related to a bat strain and were possibly caused by oral ingestion of contaminated food. After agriculture and animal domestication, three domiciled strains infected Andean populations. Geographically, the analysis of *T. cruzi* strains in modern populations raised another question. Molecular biologists identified a peculiar *T. cruzi* DNA variant called TcIDOM. This variant is associated with a significant proportion of human infections in South America, yet is closely related to wild strains in North/Central America. The molecular biologists who made this discovery proposed that TcIDOM had an origin in North America in paleo times, and was then dispersed back into South America as domiciled cycles. They recognized some problems with this hypothesis. Hunter-gatherer population densities were not sufficiently large enough to support a sustained domestic cycle. To address this question, Reinhard and Araújo (2014) reviewed the archaeology of the Lower Pecos Canyonlands and showed that the archaic population was sufficiently large and sedentary to sustain transmission at least by 5,000 years ago. At the same time, earth oven cooking technology changed the landscape to enhance the wild cycle of the

parasites between rodents and kissing bugs. In addition, dietary preferences for the wild rodent hosts of *T. cruzi* resulted in kissing bugs infesting human sleeping areas. Therefore, *T. cruzi* could have undergone a *de facto* domiciliation among archaic peoples in North America. The culmination of decades of archaeoparasitology focused on *T. cruzi* completely changed the general consensus on the origins of Chagas disease. The original theory related to animal domestication was too simplistic. Intense molecular scrutiny on the topic revealed a more complex web of host switching events relating to six strains of the parasite and involving vector transmission through kissing bug feeding and also oral transmission.

Archaeoparasitology shows that parasites emerged and reemerged throughout time. An example is presented by Kuchta, Serrano-Martínez, and Scholz (2015) who describe the emerging health challenge of Pacific broad tapeworm (*Adenocephalus pacificus*) infection. This parasite normally infects sea lions. However, the final intermediate hosts, several species of fish, are eaten by dogs and humans. As a result, dogs and humans become infected in Peru and Chile. However, *A. pacificus* has a long pre-history of infection dating to 6,000 years ago (Kuchta et al. 2015). In archaic periods, infection prevalence fluctuated with climate conditions. Infection was variable after agriculture. Therefore, human and environmental conditions resulted in emergence, disappearance, and reemergence of infection.

Some infections result in calcifications that can be recovered in burial excavations. Kristjánssdóttir and Collins (2010) review the archaeological evidence of hydatid cyst disease and present several cases found in a medieval Icelandic hospital. The tapeworm *Echinococcus granulosus* provokes hydatid cyst disease in humans and animals. In humans, the liver and lungs are the most commonly affected, but cysts can form in other tissues as well. The cysts calcify and form resistant structures. Therefore, they can be found in skeleton context. In Iceland, the parasite cycled between dogs and sheep. Sheep were the intermediate host carrying cysts and dogs were the definitive host carrying egg-laying adults. The eggs, once ingested by humans, formed hydatid cysts. Kristjánssdóttir and Collins (2010) note that hydatidosis was a widespread endemic

health problem in Iceland which became the focus of a strict control campaign by the late 1800s. The severity of the problem was clearly evidenced in hydatid cysts recovered from a 1493–1554 monastic hospital cemetery. The cases were buried in close proximity to each other which suggests that hydatidosis was a recognized syndrome. The cases included the largest hydatid cyst known from archaeological context. All of the infected individuals were 50 years or older and six were over 60 years of age. The infection was equally divided between men and women. A total of 160 graves were excavated so that calcification of hydatid cysts was achieved in 5 percent of the population. This suggests that the infection did not cause much pathology in the people associated with the cysts. However, only 20–30 percent of hydatid cysts calcify and this suggests that the percentage of the population infected could have been as high as 25 percent. This study shows how careful excavation of a large population can provide insights into the establishment of a sustained domestic cycle involving dogs and sheep that resulted in human infection.

Korean remains from the same cemeteries show an absence of parasites with skeletonized burials and ubiquitous parasites in mummified burials (Seo et al. 2010). Korean researchers have focused their work on mummies and made remarkable discoveries concerning past distribution of parasite infections (Seo et al. 2014). They combined microscope and molecular diagnoses on Joseon Dynasty (fifteenth to nineteenth century) tombs, and diagnosed four species of food-borne helminths. All of these are trematodes, or flukes, which are parasitic flatworms. The fish-borne flukes include *Clonorchis sinensis* (Chinese liver fluke) and *Metagonimus yokogawai*, an intestinal fluke. One-third of the mummies were infected with one or both of these flukes. In the upper strata of Joseon society, uncooked fish was commonly eaten. Eating uncooked crab was the infection source of the lung fluke *Paragonimus westermani*, which was found in 20 percent of the mummies. Oysters were the source of the intestinal fluke *Gymnophalloides seoi*, infecting 10 percent of the mummies. In total, 61 percent of the Joseon mummies were infected with one or more species of fluke. When the nematode

(roundworm) data are added to the picture, all mummies were positive for one or more species: 56 percent contained eggs of *A. lumbricoides* and 72 percent were positive for *T. trichiura*. Therefore, fecal contamination of the human environment was a problem, since infection can be associated with unwashed food. Pinworm was found in 11 percent, which reflect airborne or person-to-person infection within habitations. A rare parasite, *Strongyloides stercoralis*, was found in two mummies. Infection occurs when larvae of these parasites burrow through the skin. Another unusual parasite, *Trichostrongylus*, was found. The larvae of this genus must be eaten to cause infection. These last two parasites were found together in a single mummy. The pathoecology reflected by these mummies is complex with nidi, including the water sources from which fish, oysters, and crabs were collected, the fields in which plants were grown (*Trichostrongylus*, *A. lumbricoides*, and *T. trichiura*), and even the enclosed structures in which the elite lived (pinworm).

This entry reflects the maturation of archaeoparasitology. In a foundation article, Reinhard (1992) predicted that parasitology would be a tool for the archaeologist. He specifically projected that parasite data would shed light on diet, transhumance, trade, environmental contaminants, health, interaction with domestic animals, and human-parasite ecology and evolution. Archaeoparasitology has made contributions in all of these areas. However, with molecular biology as a newer diagnostic tool, the field is making strides in showing evolution of parasites through time and geographical space.

SEE ALSO: Anemia; Archaeoentomology; Archaeological Sciences; Archaeology; Bioarchaeology; Burial Excavation; Environmental Archaeology; Human Lives and Deaths; Infectious Disease; Marine Molluscs; Osteology; Ostracods and Cladocerans; Paleopathology; Palynology; Parasite Ova and Cysts; Scientific Revolutions; Water Pollution; Zooarchaeology

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Stature Estimation

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The estimation of stature—the height of an individual—is used on human skeletal remains regularly within the contexts of paleoanthropology (see BIOARCHAEOLOGY) and forensic anthropology. While researchers have continued to refine methods, most involve the extrapolation of stature from limited, fragmentary skeletal remains. These reconstructions are used to understand the impact of lifeways on individuals, document changes in diet and environmental stress over time, and develop a measure against which to scale other individual biological dimensions. Herein, the history of stature estimation is briefly reviewed, followed by a summary of current methods and their applications.

A history of stature estimation methods

For over a century, researchers have successively refined the statistical methods for stature estimation, introducing new approaches and samples to address shortcomings noted in previous methods. One significant concern driving continued research on stature estimation is that, because human groups vary in the proportions of bone lengths to total stature, accurate estimation methods are often region- or group-specific. A mismatch between the reference sample used to create estimation equations and the group to which the equations are applied may result in incorrect stature estimations. As a result, many of the studies produced within recent years have focused on minimizing this incongruity, which was established a century ago.

Estimations of stature were formalized in a consistent and repeatable scientific methodology in the late nineteenth century. These earliest methods related the lengths of limb long bones to known statures for individuals directly, generally

using ratios. Étienne Rollet, a physician and anatomist who amassed osteometric data from cadavers, was the first to develop these methods in 1888, followed by Leonce Manouvrier and Thomas Dwight, both also physicians and anatomists. Each created simple relational tables, where the length of a long bone (e.g., the femur) was listed in relation to the average total stature associated with that measurement. While these relational tables were popular through the early twentieth century, they were soon surpassed by statistical approaches.

At the end of the nineteenth century, Karl Pearson, an anatomist, biometrician, and eugenicist, utilized the then-new statistical concept of linear regression to estimate statures from the femur and tibia (Raxter, Auerbach, and Ruff 2006). Pearson's method applied ordinary least squares (OLS) regression (see LINEAR MODELS and REGRESSION AND CORRELATION ANALYSIS), where individual long bones were used to predict living stature. The sample used in this study consisted of 100 French cadavers (50 of each sex), half of which were regarded as “senile,” although decreased stature due to advanced age was not considered by Pearson to be an important factor. Pearson devised formulae for each sex, but did not take proportional differences among human groups into consideration.

Yet, biological anthropologists increasingly noted differences in body proportions between human groups in papers published during the first third of the twentieth century. Aleš Hrdlička (a student of Manouvrier) noted proportional differences between the Lenape and Europeans in the tibio-femoral ratio (later named the crural index). William Ingalls, an anatomist at Western Reserve University, followed up on Hrdlička's findings, and determined that stature estimation equations cannot be developed and applied universally due to proportional variation among human groups; he did not develop new equations. Paul Stevenson, another anatomist, finally did in 1929, creating group-specific regression equations (for the Chinese) developed to address the mismatch problem (see Raxter et al. 2006).

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Mildred Trotter and Goldine Gleser published the first widely used group-specific stature estimation OLS regression equations, first in 1952 using “white” and “black” females and males from the Terry Collection at the Smithsonian Institution. Later, they revisited these formulae for males following the Korean War, adding “Mexican” and “Mongoloid” samples. Eighteen years later, the authors published corrections for inconsistent measurements of the forearm bones in original studies. Later, Lee Meadows Jantz and colleagues demonstrated systematic mismeasurement of the tibia in Trotter and Gleser’s original studies. Thus, while these equations continue to be used, researchers have expressed caution about their application. Additional equations were soon calculated for the Japanese by Fuji, for South African groups by Allbrook, and for Mexican and Pueblo groups by Genoves. Various other groups have been added in subsequent decades. Collectively, these publications have created a body of literature promoting mathematical methods for stature estimation, all based on OLS regression of individual or a small number of skeletal elements against known statures.

At the same time as Trotter and Gleser (1952) were developing their equations, Georges Fully, a French anatomist and physician, was tasked with identifying Nazi death camp victims. Fully (1956) developed a technique for reconstructing stature by directly measuring skeletal element contributions to height and then using a correction factor to account for bone overlaps and missing soft tissue. This approach, the anatomical estimation method, relied on generally intact skeletal remains, and thus is impractical for frequent application within archeological and forensic contexts. Shortly after developing the method, and working with H. Pineau, he sought to address this by devising OLS regression equations for estimating missing vertebrae. Given proportionality differences among human groups, and a geographically limited sample, Fully and Pineau’s missing element estimation methods provided a limited solution to applying the anatomical method to incomplete remains.

Fully’s anatomical method was little used before it was revised by Raxter et al. (2006). Two exceptions are the publications of John Lundy (1985), who translated Fully’s original study, and Sculli, Schneider, and Mahaney (1990), who

used Lundy’s translated methods to develop the first mathematical stature estimation equations for human remains recovered in an archaeological context, and therefore did not present known statures. Sculli et al. (1990) reconstructed individual statures using the anatomical method, and then applied regression equations to estimate those statures from long bones. This was an approach later used by others to create regression formulae for estimating statures for groups recovered from archaeological contexts (e.g., Egyptians, North American groups, Andean groups, and preindustrial Europeans). The anatomical method continues to be tested and examined, including applying the method to fragmentary or incomplete human skeletal remains (e.g., Auerbach 2011).

Current methods

As reviewed, two approaches are most commonly used currently to estimate stature from skeletal remains: OLS regression from single or a few bones, and the anatomical approach from more intact remains. Based on citation frequency, regression-based methods are more regularly used, in part because of their utility in the case of incomplete remains. Accuracy and precision, however, are a concern in the use of regression methods. Regression allows for stature to be estimated from any osteometric dimension, but these do not provide consistent standard errors of the estimate (SEEs); long bones, such as the femur or the tibia, yield much smaller SEEs than metacarpals or metatarsals. Thus, it is important to document the estimation error for any estimate when using this approach.

The anatomical approach to stature estimation remains less commonly used, in part because it is not applicable to incomplete skeletal remains (Auerbach 2011). It has advantages over regression-based methods, as it takes stature reductions occurring with age into account, and is not subject to the mismatch problem between reference and analysis samples. While some minor differences in soft tissue thicknesses may occur among individuals, no study has documented a pattern to these differences among human groups (Ruff, Raxter and Auerbach,

2012). Thus, the anatomical approach is more universally applicable, but its requirements for skeletal completeness limit its application.

In addition to these two approaches, researchers have advocated for refinements to mathematical and statistical approaches to stature estimation. Researchers like Konigsberg et al. (1998) examined the statistical application of regression methods. Konigsberg and colleagues advocated replacement of OLS regression with Bayesian (see BAYESIAN STATISTICS) approaches, as well as maximum likelihood analysis to estimate statures. These methods are especially appropriate for estimating stature for isolated individuals from a known region or reference sample.

All of the studies documented refer to the estimation of stature in adults. Stature estimation among juveniles is a new area of study, with regression equations (based on radiographs of living individuals taken from the Denver Growth Sample) first developed by Ruff. Evaluation of these equations by Sciulli and Blatt showed them to have little difference from another sample of living individuals with known stature. Applications of these formulae to human remains from archaeological contexts are used with caution.

Applications of stature estimates

In archaeological contexts, stature estimations, regardless of method used, should be regarded as proxies for living statures, were it possible to have measured those directly. When stature estimates are applied to cases where individual identification is the goal, best practice calls for the estimation error to be reported, and the estimated stature to be combined with other sources of evidence, especially context. Provided mismatches are minimized and SEEs are small, averages for groups will generally be more accurate than individual estimates, as the latter are more statistically noisy due to variation within human groups.

Thus, stature estimations are most useful when making comparisons among groups, rather than when examining individuals. Mean stature varies among modern human groups, and the amount of sexual dimorphism in stature varies as well among groups. Mean adult statures among groups range

from 1.3 to 1.8 meters, although the upper mean continues to increase among post-industrial human groups on account of secular changes during the twentieth and twenty-first centuries. These changes are attributed to improved sanitation, better nutrition, decreased parasite loads, and reduced environmental stress. Therefore, one of the broadest applications of stature estimates to archaeological groups is the documentation of changes in these factors over time or between groups. Such comparisons may demonstrate caste or class differences between groups within a culture, or other sources of social inequality. These may also indicate changes in overall population health over time or across space.

An additional use of stature estimates is as a measurement of individual size. This is especially useful in studies of allometry, where stature is used as a standard against which the scaling of other dimensions may be determined (Auerbach and Sylvester 2011). Measures of height and size also serve an important role in developing models of lower limb kinematics in gait, and thus stature reconstructions are ideal in understanding mobility and, ultimately, the evolution of bipedal gait in humans.

SEE ALSO: Bayesian Statistics; Bioarchaeology; Linear Models; Regression and Correlation Analysis

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Trauma

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Trauma analysis in archaeological science is important because it provides insight into human behaviors (e.g., violent encounters or accidents that result in a reduction or loss of mobility) and also various cultural activities (e.g., mortuary rituals, ancestor veneration, trophy taking, and cannibalism). Connecting a traumatic injury on the body to a particular behavior or activity is challenging and involves understanding how the person was injured, why he or she was hurt, and the consequences of the trauma. Trauma analysis in archaeology requires a thorough understanding of taphonomy or what happens to a body after death due to natural and cultural processes (see TAPHONOMY), differential diagnosis, bone biology, and detailed reconstruction of the mortuary, site, and regional context.

Bones break in a variety of ways, and not all these are traumatic injuries. After an individual dies, natural physical and biotic factors cause taphonomic changes to the bone. Root etching, sediment abrasions, carnivore and rodent gnawing, trampling, and other forms of damage can mimic trauma on the skeleton. Researchers in paleontology, zooarchaeology, bioarchaeology, and forensic anthropology have conducted experimental studies to better understand and differentiate human-caused changes from taphonomic processes.

Differential diagnosis is the first step in the analysis because not all damage on bones or mummified tissue is the result of an injury. This process involves a systematic sorting out of all of the possible causes of bone changes, and then ruling out those diagnoses that do not exactly fit. Identifying traumatic injuries is a laborious process that uses an understanding of the full range of human biological diversity. Models and textbooks used to teach human anatomy and physiology often represent what

Susan Lawrence and Kae Bendixen (1992, 930) describe as “idealized” versions of the body. The problem with these representations is they do not depict the morphological variation that is present on different individual’s bones. The consequence of not teaching the full range of normal human variation in anatomy is the increased likelihood of misidentifying changes to a particular skeletal element as traumatic injury. The superficial temporal artery can cause a mark on the frontal bone, which researchers analyzing archaeological remains have misidentified as evidence of cut marks made by humans (Saul and Saul 2002, 82).

Knowledge of bone biology and biomechanics (how bones and related connective tissue respond to mechanical loads) is necessary for identifying both the type and timing of the injury. There are numerous types of injuries that can occur in the body. For example, Nancy Lovell (1997) identifies 14 fracture types for human skeletal remains. Specific fractures are a result of different forces being applied to the bone (e.g., spiral fractures, compression fractures), the age of the individual and the development of their skeletal system (e.g., greenstick fractures on children’s bones), and the location of the fracture, such as at joints (e.g., avulsion fractures). Having identified the type of fracture, it is important to determine when it occurred (e.g., antemortem (before death evidenced by healing), perimortem (at or around the time of death), and postmortem (after the person is dead) trauma). The three types of trauma are distinguished from one another because bone responds differently based on whether or not it can actively lay down new bone and the ratio of organic and inorganic material in each element. Postmortem trauma is typically considered a taphonomic process and not trauma because it happened well after the individual died. However, it is possible to cause trauma by desecrating human remains soon after death or, indeed, years after death. Most research on traumatic injury is focused on antemortem or healed injuries and perimortem trauma that happened at or around the time of death.

Interpreting the etiology or cause of a particular injury in an archaeological context is usually

the most difficult task associated with trauma analysis. Over the years, numerous studies have clarified how to identify whether a fracture was the cause of an accident such as a fall, an occupation-related injury, or a result of violence. Biomechanics, injury location, and fracture type have been highlighted as possible methods of identifying what caused the trauma found on bodies recovered from archaeological contexts, but just as important is the reconstruction of who this person was and what factors in their immediate cultural surroundings were like. The individual's lived experience can be reconstructed using other skeletal markers that include age at death, estimated sex, pathological conditions, dental and skeletal morphology, stature, and robusticity. Additionally, innovative methods for studying bones (e.g., X-ray and computed tomography (CT) scans, optical scanning, 3D modeling, isotopic analysis, and molecular anthropology), along with the reconstruction of mortuary context are crucial for identifying identity. Mortuary context reveals how the community might have viewed this individual after death. To get at this, analysis of the broader archaeological context and other sites in the region is necessary in order to better reconstruct the case history for the individual under investigation.

Often trauma analyses of skeletal remains have been very descriptive and focused on

single individuals as case studies, and while those are valuable, they are limited in aiding the full range of analytical possibilities that come with archaeological collections. The individual approach combined with the population assessment provides the necessary information for understanding the social and political factors that put people at risk for traumatic injury (e.g., captives and slaves, warriors, victims of abuse, refugees).

SEE ALSO: Bioarchaeology; Differential Diagnosis; Mortuary Analysis; Osteology; Paleopathology

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Zooarchaeology and Human Diet Reconstruction

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In 1860, the paleontologist Édouard Lartet reported “incisions” on the fossilized bones of mammals, some of them locally or entirely extinct, that had been recovered in ancient deposits near Paris and elsewhere in western Europe. The morphology of these marks, he contended, could only have been produced by the slicing of human-made stone implements into fresh bone. Lartet’s findings, set as they were amid the mid-nineteenth-century debates on the antiquity of humankind, ultimately helped establish that humans had existed long before the Earth had taken on its present form. Though Lartet was not explicit about it at the time, the marks also implied that the flesh adhering to those bones had been butchered, and presumably eaten, by humans. Since then, the reconstruction of past diets has become a fundamental component of zooarchaeological analysis.

Here, diet includes those items among the spectrum of potentially edible animal resources that are consumed by humans. The selection of a diet is influenced by a complex web of physiological, sociocultural, and ecological factors that together comprise a subsistence strategy. To reconstruct the diets of past peoples with zooarchaeological data, analysts must: (1) identify the animal remains at a site; (2) be aware of preservation biases and excavation recovery techniques and their impact on sample adequacy; (3) sort out the remains that are linked to human dietary decisions; and (4) explore how these decisions fit into the wider subsistence strategy.

Dietary reconstructions rest on the correct identification of animal skeletal (vertebrates) or exoskeletal (crustaceans, molluscs, etc.) remains. While analyst skill and experience

play an important role in the identification process, factors such as fragmentation, state of preservation, the morphological distinctiveness or uniformity of particular taxonomic groups, the quality of the reference collection, and one’s research question(s) also determine the proportion of an assemblage that eventually is, or is not, identified (see ZOOARCHAEOLOGY).

Zooarchaeological assemblages represent a sample of the remains that were originally deposited. It is therefore imperative to evaluate if the sample under study reflects past dietary behavior with any degree of fidelity. Largely outside the analyst’s control are processes that can add to, subtract from, spatially reconfigure, or otherwise alter animal remains as they transform from a deposited assemblage into a preserved assemblage (see TAPHONOMY). Careful attention to context and the application of experimentally verified linkages between specific agents and their resultant traces can help identify the impact of these processes. Field recovery techniques must also be well thought-out. Decisions about screen size, excavation unit placement, and excavated volume should be made, within the constraints set by time, money, and research goals, to ensure that the recovered assemblage adequately samples the preserved assemblage.

Faunal assemblages, even those from archaeological sites, are the result of complex amalgamations of many events, only some of which involve human agency. Isolating those animals that were deposited by human dietary behavior is thus a critical, but by no means straightforward, task. The presence of animal remains in human coprolites is a direct and unambiguous sign of ingestion. Such evidence is extraordinarily rare, however, and may not necessarily reflect dietary consumption. Much more common are the modifications produced on bones and shells by butchery and consumption, which include the disarticulation of skeletons or exoskeletons, thermal damage, breakage, cut, chop, and saw marks, percussion marks, and tooth marks. While the presence of one or more of these can signal human involvement, nonhuman agents may

create very similar traces. Again, context and the use of experimental data can alleviate, though not completely eliminate, interpretive ambiguity. What is more, many of these traces are unintentional by-products, so not all of the butchered and consumed remains actually preserve evidence of those behaviors.

Once a faunal assemblage (or some portion thereof) is securely linked to human dietary decisions, the analyst can reconstruct past menus by simply listing the consumed taxa. Another approach is to determine the abundance of various taxa and, thus, their relative contribution to the diet. The most basic quantification units are the number of identified specimens (NISP) for each taxon and the weight of identified specimens by taxon. Zooarchaeologists also typically convert NISP or weight into derivative measures that attempt to approximate the amount of animals, skeletal parts, or potentially edible biomass represented by a faunal collection. While not without weaknesses, these measures are more easily translated into estimates of food value and, thus, often serve as units of analysis in studies of dietary choice and its role within a wider subsistence strategy.

The value assigned to an animal is contingent on an array of variables that include availability, cost, individual and/or group preference, nutritional yield, and social obligations. Anthropological studies among contemporary human groups commonly incorporate this information into quantitative and semiquantitative models to understand and predict the incorporation of animals into the diet. Fortunately, some of these variables can be accessed with zooarchaeological data. Availability and procurement costs, for example, are influenced heavily by seasonality—animals may only be available, or worth the effort to acquire, at certain times of the year. Age at death, which is reflected in the developmental stage of incrementally growing structures like teeth and shells, can help determine when over the course of a year an animal died and, thus, the timing of site utilization by humans. The nutritional value of an animal varies not only by age but also by sex, and the latter can be revealed through skeletal markers of

sexual dimorphism (e.g., antlers, body size). Some animals are imbued with special cultural meaning that often affects the way they are processed for consumption and distribution. Such treatment can result in specific patterns of modifications to their remains. When coupled with other datasets, then, zooarchaeology remains a key tool for archaeologists interested in reconstructing the diets of past peoples.

SEE ALSO: Diet and Carbon Isotopes; Diet and Nitrogen Isotopes; Diet and Sulfur Isotopes; Diet and Trace Elements; Domestication; Domestication of Equids; Environmental Archaeology; Ethnoarchaeology; Experiment in Archaeology; Fish; Food Residue Analysis; Formation Processes; Fruits, Vegetables, and Nuts; Llamas and Alpacas; Malnutrition; Osteology; Ostracods and Cladocerans; Paleoenvironmental Reconstruction; Pigs; Quaternary Large-Mammal Zones; Quaternary Micro-Mammal Zones; Sheep and Goats; Taphonomy; Zooarchaeology and Ancient DNA; Zooarchaeology and Human Trade and Migration; Zooarchaeology and Stable Isotopes

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Zooarchaeology and Human Trade and Migration

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The intentional control and movement of animals and animal resources can perhaps be considered a universal phenomenon as it is found among all societies. Since animals have been a major source of food and raw materials for most if not all human societies, we can infer that people have always been transporting animals and animal resources with them as they moved across the landscape, colonized new areas, and migrated between different regions. As such, although the archaeological record is equivocal, human-mediated animal movements have surely occurred since at least the Lower Paleolithic. Because nonhuman animals have the capacity to move independently and because many species can migrate long distances, it is often difficult to discern natural animal movements from human-mediated or anthropogenic transport of animals. For example, the wild ancestors of domestic dogs (*Canis familiaris*), the oldest domesticated animal in the world, may have contributed to their own domestication by following highly mobile groups of Paleolithic hunter-gatherers, and dogs have accompanied humans as they spread out to colonize many regions of the world.

Often the clearest zooarchaeological evidence for human migrations and trade is the presence of (exotic) animal remains outside of their natural ranges, a pattern that has been documented among a wide range of societies and time periods. For example, the presence of faunal remains of marine animals (shells, bones, teeth) in non-coastal archaeological deposits can often be most parsimoniously explained as resulting from human agency. These include the acquisition and transport of marine resources, not only for food

(fish, shellfish, and marine mammals) but also as raw materials for the production of various artifacts, which is evidenced by the presence of marine remains in inland geographic settings, sometimes dozens or even hundreds of kilometers from the nearest coast (Sayre, Miller, and Rosenfeld 2016).

The transport and trade of both living animals and animal remains is also well established for many terrestrial species, based on the identification of animals far beyond the limits of their natural ranges and sometimes across natural boundaries such as mountain ranges, deserts, or large water bodies. Zooarchaeological evidence indicates that the intentional and unintentional movements of animals were widespread and included such diverse categories as parasites, commensals, and tamed (pets), wild, and domesticated species. In fact, animals that have migrated with humans or are widely traded by them, especially domesticants, have become some of the most demographically successful and widespread species on the planet, and all domesticated animals have been to varying extents moved and traded by humans. Conversely, many wild animal species have suffered from extirpation (local extinctions) or extinction by human hands, either directly from hunting, fishing, and collecting or indirectly due to a variety of causes, including the anthropogenic introduction of predators, competing or invasive species, or other effects associated with human migrations.

Species translocations are the introductions of live animals into new territories by humans often, but not always, in the context of colonization and migration. The concept of transported landscapes (Anderson 1952), although originally focused on flora, is equally relevant for fauna and refers to the transport by humans of a selected subset of a region's biota from one location to another. Examples of transported landscapes have been widely documented globally and are perhaps most archaeologically visible in cases of trans-oceanic transport, where human intervention would have been required to move terrestrial species or their remains over vast distances of

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open ocean (e.g., Laffoon et al. 2014). Perhaps the most well-known example of this process is the spread of pigs, dogs, chickens, and rats from maritime Southeast Asia to the major subregions of Oceania (Melanesia, Micronesia, Polynesia), where it is clear that no natural mechanisms could have accounted for such dispersal.

It can be difficult to distinguish between the movement of living animals and the movement of whole animal carcasses or the trade of animal parts or remains. In some cases, the presence of extant animal populations indicates that past movements included not only living individuals, but also reproductively viable individuals. In other cases, archaeological context, anatomical completeness, skeletal element representation, or evidence for modification and use can provide clues concerning the nature and function of traded faunal resources. For example, recent zooarchaeological and isotopic analysis of faunal assemblages from monumental contexts at Teotihuacan, Mexico (one of the largest ancient urban centers in the pre-Hispanic Americas) revealed the importation, captive management, sacrifice, and ritual deposition of wild carnivores, probably at the behest of local elites (Sugiyama, Somerville, and Schoeninger 2015). Similar cases of long-distance trade of animals and/or animal resources have been identified not only among other regional populations in Mesoamerica, but also worldwide. This highlights the active use and manipulation of animals in nonalimentary (social, political, ideological) domains of interaction.

The movement of living animals by humans also includes repetitive activities occurring within specific geographic ranges, such as herding, pastoralism, and seasonal mobility, which are integral to the subsistence economies of many diverse populations. These seasonal movements of animals can often be inferred via zooarchaeological datasets and related methods. Furthermore, animals and animal resources are some of the most common and widely circulated objects of exchange, and the development of large-scale networks has contributed to the movement of animal products several thousands of kilometers from their origins by ancient groups. The formalized trade of goods and products that characterizes market economies in many regions of the world has provided increased opportunities for the

flow of animals and animal products between people. In fact, one of the defining features of the Age of Discovery and of the subsequent Columbian Exchange (Crosby 1972) was the large-scale trans-continental movement of cultures, peoples, plants, and especially animals. The outcomes of these global interactions have had enormous and often irreversible impacts on the ecosphere, including the introduction of invasive species, widespread habitat alteration and destruction, local extirpations, mass extinctions, epidemics and demographic collapse, and permanently altered ecological systems. In fact, the ultimate effects of these historical processes on future environmental conditions are as yet unknown.

Traditional zooarchaeological methods and techniques including taxonomic identification and quantification have significantly contributed to our knowledge of past exploitation and use of animal resources (Reitz and Wing 1999), including the movements of fauna that occur via human migration and trade. In recent years, zooarchaeological research on these topics has been greatly enhanced by the development and application of various isotopic approaches, especially analyses of radiogenic strontium (see MOBILITY AND STRONTIUM ISOTOPES) and lead (see MOBILITY AND LEAD ISOTOPES) isotopes, as well as stable isotope analyses (see ZOOARCHAEOLOGY AND STABLE ISOTOPES) of carbon (see DIET AND CARBON ISOTOPES), nitrogen (see DIET AND NITROGEN ISOTOPES), sulfur (see DIET AND SULFUR ISOTOPES), and oxygen (see MOBILITY AND OXYGEN ISOTOPES) (Makarewicz 2016). A broad range of other biochemical (see HUMAN SKELETAL GEOCHEMISTRY) and biomolecular methods and techniques such as analyses of organic residues (see ORGANIC RESIDUE ANALYSIS) and aDNA (see ZOOARCHAEOLOGY AND ANCIENT DNA) are increasingly applied within the context of zooarchaeology (see ZOOARCHAEOLOGY) and bioarchaeology (see BIOARCHAEOLOGY). These advancements have greatly enhanced archaeological insights on human trade and migration and now permit a much larger corpus of evidence to be obtained not just from macroscopic faunal remains (bones, teeth, shells) but also from microscopic samples (proteins, lipids, aDNA). It is expected that current developments and future progress in a wide range of scientific disciplines

will continue to make substantial contributions to the increased accuracy of taxonomic identifications; expand the range of analyzable archaeological materials; and improve the identification of geographic origins and the determination of ancient routes of human migration and trade.

SEE ALSO: Birds; Bones and Ivory; Cattle; Fish; Genetics: Ancient; Genomics: Ancient; Isotopes; Llamas and Alpacas; Pigs; Sheep and Goats; Zooarchaeology and Human Diet Reconstruction

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Chromatographic Techniques in Conservation

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A recognized responsibility for conservators and scientists who work with cultural artifacts is examination, one component of which is the study of materials and manufacturing techniques. Both gas and liquid chromatography (GC and LC) are routinely applied to the characterization of certain classes of organic materials found in artifacts, and although not without limitations are the most versatile techniques for detailed analysis of many organic materials found in cultural artifacts. GC interfaced with mass spectrometers (GC-MS; see GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS)) is now a fundamental tool in many museum scientific analysis laboratories. High-performance liquid chromatography (HPLC or LC; see HIGH PERFORMANCE LIQUID CHROMATOGRAPHY (HPLC); also commonly interfaced with mass spectrometers, LC-MS) currently has more restricted applications, but will likely find more applications in the future. In addition to aiding in understanding materials used to make cultural artifacts, chromatography can play an important role in understanding deterioration or states of preservation of specific works of art, or the behavior of materials used in conservation or preservation initiatives. The preservation of cultural artifacts housed within a museum may be very dependent on the environment in which the housing takes place—display cases, storage cabinetry, air quality—and chromatographic techniques are also utilized to help evaluate this environment.

Thin layer chromatography, the earliest type of chromatography routinely used to study materials in cultural artifacts, has been largely supplanted by GC and LC. One of the earliest systematic applications of GC in the study of

works of art, published over 50 years ago, was the analysis of oils and fats in paint binding media. The compounds in fresh oils and fats (mostly triglycerides) are not easily analyzed by chromatography, but they can be broken down to yield smaller molecules (mainly certain saturated fatty acids, such as palmitic and stearic) that can potentially (along with other compounds formed during aging, such as azelaic acids) identify the nature of the original oil or fat, even when that original material has been severely altered. In works of art, oils and fats are most commonly encountered in paints; vegetable oils (those that are capable of “drying,” such as linseed, walnut, poppyseed, safflower, and tung) are the binder of oil paints. Egg yolk, another important historical paint binder in some parts of the world, contains a significant oil component.

Oils and fats are of considerable interest to archaeologists, and similar GC-MS analysis and sample preparation techniques are used for very old archaeological materials and comparatively much newer easel paintings created over the last few hundred years. Decades of GC-MS analysis of oil paintings in Europe has elucidated the history of the use of different oils; coupled with understanding of how different oils change upon aging, these have provided insights into choices made by individual artists. Medieval and early Renaissance Italian oil painters, for example, sometimes used two types of oil in single paintings—one (linseed) dried more quickly than the other (walnut), but the slower-drying one yellowed less during aging, a fact apparently understood by painters, who would use it with colors where yellowing would noticeably affect the color of a paint over time (whites turn yellow, blues darken or become greenish tinted).

Although egg yolk also contains some oil, its major components are proteins. Binders consisting entirely of proteins include egg white and animal glue (made up of the protein collagen). Proteins are complex molecules built from about 20 types of amino acids. Although many proteins contain the same amino acids, the relative amounts vary from one type to another. Hydrolyzing a protein into its constituent amino

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acids, then separating and quantifying these by chromatography is a traditional method by which proteins have been and continue to be identified. Quantitative amino acid analysis by GC-MS (or, less frequently, LC) works well for distinguishing between some of the most common proteins in cultural artifacts. Egg has been identified as a paint binder, for example, in wall paintings from the 3000–2400 BCE Sos Furrighesos necropolis in Italy (Rampazzi et al. 2002) and the 1200 BCE Palace of Nestor in Pylos, Greece (Brecoulaki et al. 2012); and on figures from the “terracotta army” of emperor Qin Si Huangdi (259–210 BCE) (Bonaduce et al. 2008).

Glues, which contain collagen that can be easily extracted from connective tissues and other parts of many animals and from some fish, were common adhesives and binders in many parts of the world.

Among the limitations of amino acid analysis are the inability to easily distinguish between egg yolk and egg white, between different avian sources for eggs, and between different animal or marine sources of glues. Despite these limitations, amino acid analysis techniques by GC-MS will continue to be important in the future. Early identifications depended on the presence or absence, and relative abundance, of certain amino acids; statistical analysis has now become more common.

Another major class of binders that consists of very large molecules not directly amenable to analysis are plant gums, which consist of complex carbohydrates. These molecules can easily be hydrolyzed into simple sugars (monosaccharides), the small molecules from which they are formed. Analysis of monosaccharides (and uronic acids) liberated from plant gums has been a common method for identifying plant gums in cultural artifacts by GC-MS, and it remains the best of the currently available instrumental analysis methods for this purpose (Lliveras-Tenorio et al. 2012). There are less than a dozen common monosaccharides found in plant gums, and many of the same ones are present in different gums, so identification of a specific gum through monosaccharide analysis is not always straightforward. A study published over 40 years ago concluded, from GC analysis of monosaccharides, that fruit tree gums were utilized in some central Asian paintings dated back nearly two millennia. More

recent analyses have shown that plant gums were apparently common in ancient Egyptian tomb paintings, perhaps at least in some instances a type of *Acacia*, a genus from which the gum still used in artists’ commercial watercolor paints (*Acacia senegal*) is derived.

A class of natural materials very important in the archaeological and art fields is natural resins, exudates (insoluble in water) that come from many different types of trees. In the nineteenth and earlier part of the twentieth century, natural resins from many parts of the world were major constituents of commercial varnishes. Most natural resins exude from their source plants as very viscous liquids, often becoming hard, somewhat sticky solids after their natural solvents evaporate. They can be softened by heating, and in this semi-liquid form can be used as adhesives. Possibly the earliest use of natural resins may have been as adhesives to attach arrow points to wooden shafts. A type of *Pistacia* resin, from shrub-like plants that grow in northern Africa and elsewhere, has been identified as a varnish on ancient Egyptian sarcophagi. It evidently was melted and applied thickly and unevenly as a viscous liquid, often only to certain painted passages. Most natural resins undergo many chemical changes as they age, and the *Pistacia* on Egyptian objects is now dark and very yellow, undoubtedly much yellower than it had been when first applied. As an original component of a sarcophagus, conservators would not remove it even if it is somewhat disfiguring and considerably altering the appearance of the underlying paint. Another type of *Pistacia*, possibly not the same species as that used in ancient Egypt but chemically very similar, was a popular varnish for paintings in the nineteenth and twentieth centuries. Old natural resin varnishes, usually yellow, significantly affect the appearance of the underlying paint. As non-original components of paintings, these old varnishes are usually removed. GC-MS analysis is the analytical method of choice for identification of natural resins in all contexts. Specific resin identifications can be very important to a conservator’s decision regarding cleaning procedures. Some remnants of early original natural resin varnishes have been found in inconspicuous or hidden areas on Renaissance panel paintings, having survived cleaning procedures over the years. The study

of these, usually by GC-MS, sheds light on the nature of early picture varnishes.

Natural resins have been used for many purposes throughout the world and throughout history. In central America, resin used by the Aztecs as an adhesive, among other purposes, has been identified as a *Bursera* species (Lucero-Gómez et al. 2014). A very unusual natural phenolic resin, locally known as mopa mopa, was mixed with pigments by the Inka to decorate ceremonial qero cups (Newman, Kaplan, and Derrick 2015).

Natural resins were sometimes mixed with oils to modify the handling properties or appearance of the oil paint. Small traces of natural resins can be readily detected in small paint samples by GC-MS, and provide insights into the ways in which painters have manipulated their media for various purposes.

Limitations of traditional GC that impact or complicate its applications to cultural artifacts are that compounds must be analyzed in the gaseous state. In practical terms, this means that molecules must be relatively small and must be chemically stable at the temperatures commonly used with GC instruments (up to 300 °C). In the case of proteins and plant gums, large molecules not amenable to GC can be broken down into smaller compounds. These are still not directly amenable to GC, but can be reacted with various chemicals (derivatized) to forms (derivatives) that can be analyzed. (This is the case, for example, with amino acids and monosaccharides, and acidic compounds found in oils and resins.)

A pyrolysis (Py) attachment can be added to GC-MS instruments (Chiavari and Prati 2003). This permits small solid samples to be heated (in an oxygen-free environment), sometimes in the presence of a derivatizing reagent, to a very high temperature (typically 500–800 °C) that breaks down (pyrolyzes) large molecules into smaller fragments. The smaller fragments are then separated in the GC instrument. This procedure can be applied to virtually any complex molecule, protein and complex carbohydrates included, and is a relatively straightforward means of analyzing many samples. Another advantage is that vastly different classes of materials can be simultaneously detected, although often not specifically identified. Traditional GC sample preparation

requirements often work on one class of materials, but other samples would be needed for other classes of materials, ultimately requiring multiple samples and considerable labor.

Amber, the general name for fossilized resins, is virtually insoluble in all common solvents, and consists, for the most part, of polymeric material. Yet Py has proven to be an excellent method by which different types of ambers can be identified.

One unusual natural material, which utilized the sap from several types of trees that grow in a number of Asian countries, is lacquer. The sap, whose chemical composition has only been elucidated recently in any detail, forms a solid, impervious film when exposed in fairly thin layers to air at a certain relative humidity. Due to clear compositional differences, the major types of lacquer plants can be easily distinguished by Py GC-MS. In recent years, a systematic study of export lacquer objects, made in Asian countries for the European market, has utilized Py GC-MS to characterize (at least in part) the astonishing number of components that could be present in a single lacquer sample, which could include more than one type of natural lacquer, oil, natural resins, and proteins (Schilling et al. 2016).

Towards the end of the nineteenth century, the fledgling chemical industry began to develop many synthetic materials, including modified natural materials (cellulose nitrate, for example) and entirely human-made substances, such as synthetic dyes and pigments. Plastics were embraced almost as soon as they were invented by some artists, and characterization of these synthetic materials, which often exhibit significant conservation problems, is important. Py GC-MS has proven to be one of the most useful techniques to identify plastics. Synthetic paint media were first used by some artists in the 1930s and 1940s, and in the 1960s acrylic emulsion artists' paints came into use. Acrylic emulsion paintings present unusual cleaning problems to conservators, and research on such emulsions in the conservation field often involves GC-MS and Py GC-MS as major analytical tools. The plastic substrates of modern sculptures also have been studied.

Another type of sampling procedure, most often used in conjunction with GC-MS, is solid-phase microextraction (SPME), which was

invented in 1989. It “collects” certain organic compounds onto a solid fiber (the compounds can be in a water solution, or in air). The solid fiber is placed in the GC inlet and the trapped compounds desorbed by heating, then separated in the GC. In the conservation field, the technique is being actively explored as a means of identifying and possibly quantifying certain compounds that are released by materials used in constructing storage or display cases for cultural artifacts. Cases are often fairly (or very) airtight, and volatile compounds given off by materials of construction may become concentrated in the case. Some of these (for example, formic and acetic acids and formaldehyde) are known to be potentially hazardous to some materials that have been used to make artifacts. SPME provides one means of identifying a range of volatile compounds given off by case construction materials (fabrics, plastics, wood products, etc.)

HPLC and LC-MS techniques have far fewer routine applications in museum science laboratories at this point in time than GC-MS techniques. Over 30 years ago, LC was first applied to identification of natural dyestuffs in textiles, and it is currently the technique that can provide the most detailed compositional information on natural (and many synthetic) dyes. Natural dyestuffs in particular often contain numerous compounds, making chromatography a logical approach to their full characterization. As in the case of GC-MS, many laboratories throughout the world utilize generally similar chromatographic procedures, meaning that LC or LC-MS data from one institution can often be directly related to those from another institution. As one example, there are several natural dyes that are extracted from insects (cochineal of several types, kermes, and lac are the main ones) and these can be readily distinguished individually or in mixtures by LC. Some textile dying involves simultaneous use of dyes of several kinds, and LC can often unequivocally identify all of them during a single analysis.

LC was recently used to identify the presence of indigo in 6,000-year-old cotton fabrics from Huaca Prieta on the northern coast of Peru (Splitstoser et al. 2016), in a region in which cotton was first domesticated, perhaps a century or more before the time when the indigo-dyed fragments were made. The same major compounds are

found in indigo dyes from many types of plants that grow in various parts of the world, but the Peruvian source may have been an *Indigofera* species. From this same relatively arid region of South America are the stunning early dyed textiles from the Paracas culture. Among the very well-preserved dyes are reds derived from a type of madder plant. Many plants given this general name are known and have been used throughout the world. The native South American types probably belong to the *Relbunium* genus.

Ion chromatography (IC), a form of HPLC, has been used to identify anions associated with deterioration of monuments, in runoff water or in corrosion products. Quantitation of formic and acetic acids in the air inside storage or display cases can be carried out by IC analysis of the acids captured with specially prepared diffusion tubes. Size exclusion or gel permeation chromatography (SEC or GPC), other forms of HPLC, have been used to determine molecular weight distributions of materials in conservation and preservation studies.

SEE ALSO: Chromatography and Archaeological Materials Analysis; Dyes; Mass Spectrometry (MS); Organic Residue Analysis; Pigments and Binders

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Conservation

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What is conservation?

Conservation is defined as “all measures and actions aimed at safeguarding tangible cultural heritage while ensuring its accessibility to present and future generations.” This definition was adopted by the International Council of Museums–Committee for Conservation (ICOM-CC), in 2008. It reflects the fundamental document that describes what conservators do, *The Conservator-Restorer: a Definition of the Profession* (ICOM-CC 1984) that “set forth the basic purposes, principles, and requirements of the conservation profession.” It also reflects the principles that have guided the activities and aims of professional conservation practice since UNESCO auspiced the establishment of the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICROM) in Rome in 1959.

The activities of conservation include technical examination, preventive conservation, remedial conservation, and restoration framed by the philosophy that all conservation action must respect the physical properties of the object and its significance. These basic tenets of conservation are defined within professional codes of ethics and codes of conduct around the world (see ETHICS IN CONSERVATION).

The *Definition of the Profession* provides the framework for the ways in which conservators work together, and also with other professions and disciplines, in order to “comprehend the material aspect of objects of historic and artistic significance in order to prevent their decay and to enhance our understanding of them so as to further the distinction between what is original and what is spurious.” Being able to discern what constitutes an authentic cultural record is an essential part of conservation and archaeological

professional practice, and is the basis of all academic enquiry and good scholarship.

Conservation and archaeology

Conservation and archaeology are, essentially, interdisciplinary activities, and the tenets of conservation, thorough examination, minimization of risk, preventing deterioration and damage, and respect for cultural and historical significance, are the responsibility of all professions involved in ensuring access to and study of heritage (Matero 2008). Conservation provides the frameworks, evidence, and knowledge to ensure that decision making involving the preservation of the cultural record is properly informed and rigorously assessed.

Archaeologists and conservators share an obligation to properly document and preserve the cultural and scientific records with which they engage. Both disciplines seek to interrogate materials, investigate their condition, and understand their production, in order to uncover, present, and preserve information about the past. Sharing knowledge and providing cross-disciplinary education and advice is important from the time archaeological material is first uncovered, until it is finally located in a study collection or exhibition. While many archaeological excavations may not have a conservator on site, the conservation profession retains its responsibility to provide education, advice, and develop standards that reflect this shared responsibility.

The conservation process

Examination

A comprehensive technical examination is the first step undertaken to understand the object, to best manage its condition, and inform decision making. Examination is “the preliminary procedure taken to determine the documentary significance of an artefact” (ICOM-CC 1984). During examination the original structure and materials of the object are assessed, and the findings, along with any determination of the

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extent of any deterioration (DETERIORATION), alteration, and loss are documented. This process is critical in ensuring verifiable evidence-based decision making.

After the initial examination is complete a research or treatment pathway can be determined, and where necessary the analytical pathway can be proposed. As a general principle examination and analysis proceed from basic visual analysis to the utilization of lab-based techniques and then to high-end analytical techniques. This means there is not one defined analytical pathway relevant to every investigation, and only in specific cases is complex analysis required.

Documentation

Documentation in conservation is “the recording in a permanent format of information derived from conservation activities” (AIC 2016) (see CONSERVATION DOCUMENTATION). Good documentation supports all levels of decision making in conservation and is essential in providing information about the object, its condition, and any past intervention or modification. Established procedures for conservation documentation include the preparation of a condition report that identifies the object, its context, and its condition, and includes recommendations for its future care. In the case of a collection or site a collection survey will provide the same information. Documentation will usually include photographs of the object and may also include a technical examination report comprising scientific analytical findings (see OPTICAL MICROSCOPY; RAMAN SPECTROSCOPY IN CONSERVATION; and OPTICAL SPECTROSCOPIES) as well as a treatment report that documents any conservation intervention undertaken on the object and data associated with technical analysis, such as spot testing or infrared spectra (see MICROCHEMICAL TESTS IN CONSERVATION and RAMAN SPECTROSCOPY AND MATERIAL ANALYSIS). It is important that conservation documentation adheres to industry standards so that object identification and research dissemination are unambiguous. Glossaries that assist with the description of materials, methods, deterioration, and conservation activity are provided by ICOM-CC, IIC and national bodies such as the American Institute for Conservation (AIC) in the United States, and

the Institute for Conservation (ICON) in the United Kingdom, and others. Object ID (ICOM n.d.) is used globally as an agreed format for object documentation, and the ICOM/CIDOC Documentation Standards Group, 2017 Definition of the CIDOC Conceptual Reference Model (ICOM/CIDOC Documentation Standards Group 2017) is another useful tool for the documentation of heritage.

Conservation research

Rigorous research enables good evidence-based conservation practice, which is critical when conservators are making decisions about treatment, risk management, or providing advice to other professionals such as archaeologists. By its very nature archaeological material will have been subjected to chemical, biological, environmental, or physical factors that will have impacted on the condition of the material as well as, potentially, on the ability of researchers to study this material. Different classes of materials respond in different ways to their environment. A piece of glass lying in a salt-rich damp environment, for example, will behave very differently to one in a dry tomb environment (see CONSERVATION OF VITREOUS MATERIALS). The method of manufacture will also affect the reaction of the object to the environment, both physically and chemically. Objects achieve equilibrium with their environment and the changes involved when objects are removed to a stable museum-standard environment may severely damage the object. Conservation research, therefore, brings together an understanding of the construction and materials comprising the object, with an understanding of the effect of different environmental conditions, and of deterioration processes, and combines this with knowledge of possible preservation or treatment options, in order to properly inform decision making about excavation, transport, storage, treatment, and display. Conservators work closely with scientists in various fields to employ relevant techniques (see ELECTRON MICROSCOPY IN CONSERVATION; GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS); and INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)) and conservation scientists provide special

expertise within the profession (CONSERVATION SCIENCE).

Preventive conservation

Following examination and the completion of relevant documentation a decision can be made whether to preserve the object without treatment, or to undertake remedial conservation or a more interventive restoration. This is an important distinction. Preservation seeks to minimize any need to intervene in the physical structure of an object. ICOM-CC's *Definition of the Profession* describes preservation as "action taken to retard or prevent deterioration of or damage to cultural properties by control of their environment and/or treatment of their structure in order to maintain them as nearly as possible in an unchanging state" (ICOM-CC 1984). Preservation programs are supported by a range of policies and procedures that address environmental conditions, ensure safe handling and maintenance procedures, deliver integrated pest management and manage risk, including emergency preparedness and response, and in cases of digital records, the migration, reformatting or duplication of these records (AIC 2008). An example of preservation on an archaeological site could include the use of anoxic enclosures, relative humidity buffers to provide stable environment suitable for a salt-laden potsherd or keeping waterlogged material at the correct saturation to prevent damage (see CONSERVATION OF WATERLOGGED MATERIALS). Conservation triage is a short-term preventive measure that ensures the object is secured while longer term preventive or treatment options can be assessed.

Conservation planning

Conservation plans are produced as part of a preventive conservation program, but may include recommendations for conservation treatment (see CONSERVATION PLANS). In archaeology, conservation plans may involve a site management plan for material left in situ, a packing and transport plan to move items from the site to a storage facility, and a long-term conservation management plan for material held within an institution or in long-term storage. A conservation plan may also include recommendations for prioritization

of treatment or interventive conservation, and will provide advice on various possible actions.

Treatment

Conservation treatment involves direct intervention aimed at retarding or preventing deterioration. There are a number of levels of intervention within conservation treatment including remedial conservation and restoration.

Remedial conservation

If the object is unstable or damaged then a decision may be made to undertake remedial conservation, described as "all actions directly applied to an item or a group of items aimed at arresting current damaging processes or reinforcing their structure" (ICOM-CC 2008). Remedial conservation is interventive but primarily aimed at stabilization.

Restoration

Restoration, on the other hand, is primarily concerned with intervention to an object that is generally stable but which can no longer be properly visually or structurally understood. Restoration is specifically aimed to facilitate a better understanding and appreciation of the object, and support its continued use. While most restoration modifies the appearance of an item, restoration undertaken by a conservator is based on respect for the original material and manufacture, and is only undertaken when the significance of the object has been compromised by previous alteration, damage, or deterioration. An example of restoration could include infilling loss in a pot and inpainting the fill to make it less conspicuous so that the original esthetic of the piece can be appreciated.

Conservation specialization

Conservators generally work within a particular specialization such as paintings, paper, objects, or textiles, or as conservation scientists focusing in particular on scientific examination and assessment. ICOM-CC has 21 working groups that reflect special interests in areas that

include object types such as Graphic Documents, Objects from Indigenous and World Cultures, and Paintings; areas of practice such as Preventive Conservation, subjects such as Documentation, Education and Training in Conservation, and Scientific Research; and others. One group, Wet Organic Archaeological Materials (WOAM) is concerned with the degradation and conservation of organic archaeological objects found in wet or damp sites, researching and advising on in-situ conservation, reburial, and site surveys, as well as postconservation treatments of objects of organic archaeological materials (see ENVIRONMENTAL MANAGEMENT WITH FIRE).

Finally, conservators are also concerned with the conservation history of an object. The need to understand the location and effect of previous interventions is an important one. For example, adhesives degrade and often numerous layers of different adhesives exist on one object (see POLYMERS IN CONSERVATION). Some remain reversible and do not affect the object; others cross-link with age, becoming increasingly irreversible; and others become tacky attracting dust, or become embrittled, causing lifting and sheeting of surface and edges. Understanding the effect of previous interventions, including their deterioration pathways, and the possible options for removing them in the future, is essential prior to any conservation work.

SEE ALSO: Charcoal and Wood Analysis; Conservation in Museums; Conservation of Bone, Horn, and Ivory; Conservation of Earthen Building Materials; Conservation of Fibrous Materials; Conservation of Metals; Conservation of Mosaics; Conservation of Polychrome Natural and Architectural Surfaces; Conservation of Stone and Petroglyphs; Deterioration of Earthen Building Materials; Deterioration of Metals; Deterioration of Mosaics; Deterioration of Stone and Petroglyphs; Deterioration of Vitreous Materials; Deterioration of Waterlogged Materials; Deterioration of Wood; Elemental Analysis of Pottery; Heritage Ethics; ICP-MS and Material Analysis; TEM and Archaeological Materials; Thermoluminescence; X-Ray Radiography and Material Analysis; XRD and Materials Analysis

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Conservation Documentation

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Heritage conservation activities are varied and expansive, hence the documentation performed in each of these activities can vary a great deal. Conservation work is performed on heritage materials found in museums, cultural institutions, archives, and in situ. It spans the gamut from paper-thin to architectural and monumental, made from inorganic, organic, and composite materials, as well as virtual or electronic. For the purpose of this publication we will concentrate our attention on the physical world and on objects made from organic and inorganic materials.

Conservation activities can be categorized in different ways such as: condition reporting, preventative, intervention or remedial treatment, and academic (scholarly and research). According to the type of conservation activity being performed, different types of documentation can be generated. Documentation is defined as creating a physical or virtual record of the history, condition, examination, and research of an artifact that can be created in various forms such as: image-based, text-based, and data-based (analytical results). The different conservation activities can generate any or all of the documentation types just mentioned. The documentation types are not mutually exclusive and in most cases are used in combination, normally giving more weight to one type of documentation while the others have a supporting role. For example, if a conservator is to create a condition report of an art object, then the main type of documentation generated is most likely to be image-based condition reporting in which annotating and mapping of an image would be the main method used to describe the object's physical condition. Additionally, a text narrative could be used to explain condition, not readably visible on the image, and when further explanation is needed

to describe a more complex condition. Another example would be the surveying of an archaeological site using aerial photography; images obtained during this process are then used to generate photogrammetric models that provide accurate measurements and information on the site.

Documentation performed during condition reporting should reflect the state of the heritage material at the time of its inspection. Using image-based condition reporting means that images are annotated and conditions are mapped either by hand in a physical print(s), or digitally with the use of tablets or handheld computers, to represent different attributes present in the object. This documentation can be done most efficiently through a well-established imaging protocol, that involves a consistent approach to a number of steps from image capture, color processing, and naming, to storage, just to mention a few. This report also contains the tombstone information related to the object and when necessary a descriptive narrative of a condition not observed in the marked images. Condition reporting is heavily used during the loaning and borrowing of a heritage object. The lending and receiving institutions use this documentation to track and monitor any physical changes that may take place on an object during its transportation and handling through time and the participating venues.

When a heritage object undergoes examination and treatment, documentation is done at different stages of the process. This includes images of the object before, during, and after conservation treatment, recording the state of the object at each phase of the intervention, including a record or description of techniques or procedures involved, materials used and their composition, and the nature and extent of all alterations. In many cases before the treatment commences a thorough examination of the object is necessary. This may include technical examination through the use of microscopes or high magnification equipment, X-ray imaging, as well as noninvasive and nondestructive scientific analysis like X-ray fluorescence (XRF)

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and fiber optic reflectance spectroscopy (FORS). During this initial examination documentation can and should be generated in the form of images, spectra, graphs, datasets and text, whenever possible. This initial documentation should provide support and guidance during the course that the conservation treatment takes place. This information should be compiled in the treatment proposal document explaining the planned treatment and procedures, alternative approaches, and the potential risks.

Documentation of heritage materials needs to contain all pertinent information pertaining to the cultural property in question, as complete and accurate as possible. These records should include all the images, diagrams, maps, GPS location, text narratives, condition reports, sampling areas, scientific analysis, as well as description of structure, materials, and relevant treatment history. All documentation should clearly describe and identify (accession number, series, owner, etc.) the heritage property, the individual(s) involved in the treatment and examination, at all stages of the conservation work, and the dates in which examination takes place. This information can be attached to the physical object's dossier or in a digital archive storing digital documents, images, and datasets, when possible if these electronic files support metadata fields they should be populated with the pertinent information.

Documentation needs space to be stored and archived. In many instances we only think about the generation or production of the documents that make the documentation body, but it is as crucial to think about the storage and long-term archiving of this body of knowledge since it becomes an important part of the stewardship of the heritage property. Using the previous examples, the image-based condition reporting will generate marked images and text documents that can easily be saved as printed physical documents or as open source digital documents that are easily accessible by any computer system like a .pdf document and a .jpg image, requiring relatively small physical and digital storage space. In contrast, the photogrammetric approach taken for the land survey generates datasets that are very large in volume. Typically, a series of images are combined to generate files that are very large in size. These are impractical to print, and in their digital format are very heavy in data due

to the tridimensional models that they generate. As a result, their digital storage space needs are very large, and furthermore accessing and working with these files requires specialized software and greater computing power to be used efficiently.

Documentation should follow guidelines established under a well-defined framework; these guidelines can be specific to an institution or organization so as to achieve consistency and uniformity in the information generated, as well as in the way that it is stored. Guidelines have been established by professional institutions like the American Institute for Conservation of Historic and Artistic Works (AIC). In the *AIC Code of Ethics* we find that documentation is expressly stated under section VII: "The conservation professional shall document examination, scientific investigation, and treatment by creating permanent records and reports" and it is more specifically delineated in the *Guidelines for Practice* under the section titled "Documentation" where it states that "The conservation professional has an obligation to produce and maintain accurate, complete, and permanent records of examination, sampling, scientific investigation, and treatment..."

What this abiding principle does not state is the form and content of the documentation. It is then incumbent on individuals, organizations, and institutions to establish the best way to represent their heritage, and comply with this code of ethics.

In conclusion, we can say that conservation documentation is used for: establishing the condition of cultural property; providing information important for the understanding and past and future treatment of the object; helping with the appreciation and understanding of an object's aesthetic, conceptual, and physical characteristics; and providing knowledge and a permanent record that can avoid misunderstanding and litigation.

SEE ALSO: Archaeological Photography; Computational Photography; Conservation Science; Digital Photogrammetry; Drones; Electron Microscopy in Conservation; Image-Based 3D Modeling; Imaging; Infrared Reflectance Spectroscopy; Multispectral and Hyperspectral Imaging; Multispectral and

Hyperspectral Imaging of Artworks; Multi-View Stereo; Optical Microscopy; Photogrammetry and Stereophotogrammetry; Photoluminescence of Egyptian Blue; Reflectance Transformation Imaging (RTI) in Conservation; Underwater Three-Dimensional Laser Imaging; X-Ray Radiography; X-Ray Radiography and Material Analysis

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Conservation in Museums

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Introduction

The discipline of conservation in museums today must be understood within a number of different contexts. First, consideration must be given to: first, how the discipline itself evolved; second, the nature of the cultural heritage housed in particular types of collecting institutions, including how, where, and when it was acquired; and third, the purpose envisioned for the institution and its constituencies. These aspirations and activities are surmounted by the overarching responsibility of all collecting institutions to preserve and protect the materials of heritage for future generations.

The scope of conservation in museums reflects the missions of those institutions, focusing on collecting, accessibility, and preservation. Particularly in the West, archaeological collections formed through excavation center on care, preservation, and education, rather than collecting. For university collections, particular emphasis is given to pedagogical activities, research, and training, requiring more handling and use of materials than is typical in other kinds of collections. As illicit activities commonly associated with early collecting practices are increasingly scrutinized and corrected, emphasis has shifted to preservation and accessibility. Without material evidence gained through scientific excavation, the research value of such objects is greatly diminished, as is the research value of their sites of origin. Nevertheless, looting of antiquities and their acquisition by some collecting entities persist. Conservators and conservation scientists work with curators to explore material aspects of objects such as old restorations, burial encrustations, and residues, to help establish

provenance, aiding in the clarification of the history of objects. This evidence plays a critical role in determining whether objects should be acquired or retained in museum collections today.

Forming collections

The history of collecting traces back to the valuing of the rare and beautiful—for adornment, ritual practice, and preservation in ancient burial practices. Certainly the spoils of war were collected and revered over time; houses of worship preserved treasured objects and relics, and privately owned cabinets of curiosities proliferated by the seventeenth century. By the eighteenth century, the study of the antique became a serious profession, coinciding with astonishing finds from Herculaneum, Pompeii, Egypt, and other sites in the classical world, necessitating more formal museums, and a more formalized approach to care and preservation. In 1683, the donation of a private collection formed the nucleus of the Ashmolean Museum at Oxford, regarded as the first modern museum.

Archaeological collections in museums were amassed by participation in excavations and expeditions, and also by gift or purchase. The earliest excavations, lacking in rigorous documentation or any awareness of the importance of preservation, lost valuable information. Today, archaeological methodologies, and the preservation of context, are essential in our understanding of societies through objects preserved in collecting institutions. However, an inherent tension exists for these collections; when incorporated into an art museum, objects may be presented in an idealized rather than purely informational or educational light. These choices impact treatment decisions, the preservation of research potential, how objects are visually presented, and how artifacts are sampled, handled, and utilized.

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History of care and restoration of collections

The earliest origins of the discipline are found in several arenas, include the skills of craftsmen fabricating tools, structures, and objects of daily use, and fine artists creating adornments and objects of devotion. The instinct to preserve, repair, and refurbish items of value, and ritual practices performed in the burial of loved ones and dignitaries forms the basis of the modern discipline of conservation. As early as the first century BCE in *De Architectura*, Vitruvius commented on the importance of environmental damage to archival materials and objects. W. Newton's translation of this text into English became available during the late eighteenth century, and may have resonated with observers of the effects of burial, storage, display, or industrial environments on the appearance and condition of artifacts. Along with Homer's description of smoke damage to Odysseus's armor in Book 19 of the *Odyssey*, these can be considered the earliest acknowledgment of the importance of preventive conservation.

Although reuse and repair of ancient monumental or sculptural stone and other materials is documented throughout history, it is clear that as early as the thirteenth century, renowned artists like Arnolfo di Cambio had already employed the practice. Renaissance artists considered it a right of passage to "restore" ancient works of art, and many artists of the day, including Donatello, Verrocchio, Michelangelo, and Cellini, practiced the art of restoration in diverse media. Repair evolves into increasingly sophisticated and sometimes intentionally deceptive practices whose intention was to mislead the viewer about condition, age, materials, or other characteristics.

Once museum collections were established, observation of the deterioration of objects from excavations factored into the development of the modern discipline, closely allied with the development of chemistry, physics, and other sciences. A robust tradition of restoration developed alongside the introduction of chemistry applied to the preservation of museum collections. Museums sponsoring excavations in the late nineteenth to twentieth centuries managed the handling,

preparation, packing, and shipping of sensitive objects in the field, compounded by the rigors of handling, travel, and fluctuating environmental conditions. No one was more critical to this development than Friedrich Rathgen, who, in 1888, became the first Chemist-in-Charge at the Chemical Laboratory of the Royal Museums of Berlin. Extensive deterioration of bronzes and stone prompted the director to consult chemist Otto Olshausen, who formed the first true conservation laboratory. Shortly after, he published *Di Konservierung von Alterumsfunden* (*The Conservation of Antiquities*), which, translated into English in 1905, became the cornerstone of the developing field of conservation in the English-speaking world.

The collector or curator, observing alterations in objects, especially deterioration, endeavored to understand and correct such problems. In Baltimore, Henry Walters amassed one of the most significant collections of ancient bronzes in the United States, establishing the Walters Art Gallery in 1904. Shortly after his death in 1931, a scientific laboratory was established there, to understand and mitigate the damage observed by "corroding canker," today known as "bronze disease," or active chloride corrosion. In 1895, this condition had been thought a contagious disease requiring sterilization, treated at the Museum of Fine Arts, Boston (MFA) with the help of Dr. Harold C. Ernst of Harvard Medical School (Figure 1).

Development of technical study

By 1813, Humphrey Davy, inventor of electrochemistry, investigated the composition of pigments from an ancient color shop in Pompeii, drawing comparisons between those and other colors found in ancient buildings in Rome. By the mid-nineteenth century, the National Gallery of London was concerned enough about the effects of pollution on paintings that eminent scientist Michael Faraday was consulted.

After finding antiquities stored underground during World War I drastically altered, a scientific laboratory was instituted at the British Museum in 1918, to aid in understanding the



Figure 1 William J. Young, founder of the Department of Restoration, later the Research Laboratory, at the MFA, formed in 1929.

deterioration and to develop methods of repair, restoration, and preservation. The idea that museums were the proper depository for the world's treasures stemmed from a colonial bias that only the elite could properly care for these precious objects, whose history was not merely that of their country of origin, but all of western civilization.

In Europe, chemists formed scientific departments to address problems of deterioration evident soon after objects were excavated, such as damage from soluble salts and the “canker” of copper alloys. Around the turn of the twentieth century, Rathgen published treatment methodologies for vast quantities of salt-laden Babylonian clay cuneiform tablets in perilous condition.

Objects arrived in museum collections already treated in the field. Such treatments were conducted with limited resources and time. Although many objects would not have survived untreated, subsequent conservation focuses on challenges caused by those treatments, rather than original condition problems. These materials are equally important when considering further treatment, storage, display environments, and future analytical work. The limited excavation history of many objects compromises our understanding of the chemical constituents around the object, and

their possible origins—original, burial, treatment, storage, or display.

In an art museum, the ways in which an object is interpreted, treated, displayed, or stored may be determined on aesthetic or historical grounds, rather than in consideration of inherent research potential. Treatment may involve complete restoration or aesthetic reintegration, allowing the object to be seen as intact. Such decisions are based on the curator's understanding of the material at a given moment in time, and may change as new information comes to light or analytical techniques provide previously inaccessible information. University collections consider the pedagogical and research potential of objects, illustrating concepts in the history of art and archaeology and inspiring students through the experience of learning from artifacts made by ancient craftsmen.

Examination and technical study

Modern museum conservation laboratories perform: examination, documentation, treatment, and preventive conservation. Objects are examined when considered for acquisition by gift or purchase, for exhibition or loan, when questions arise about condition, alteration, state of preservation, past treatment, or restoration, or arising through new information or technologies. Provenance issues concern many museums. The MFA's Curator of Provenance researches the provenance of objects in the collection, as well as those considered for acquisition. Conservators provide material evidence used in support of the conclusions reached about the provenance of each work.

Examination begins with visual inspection under magnification, identifying original materials, burial deposits, damages, interventions or alterations, physical weakness, or chemical instability. Reflectance or luminescence of the object viewed under different wavelengths of light (such as ultraviolet or infrared) reveals important information about original materials and past treatments, including the nature of pigments, resins, or adhesives not visible under normal lighting conditions.

Radiographic methods visualize cracks, joins, and internal structures, revealing the nature and extent of interventions and restoration. Dense materials such as stone and metals require high energy to penetrate, requiring additional imaging methods, for example, gamma radiation. Ground-penetrating radar has proved useful in detecting cracks and pins in objects. Other techniques such as neutron transmission imaging may detect organic materials within metal objects, and letters written on papyri scrolls from Herculaneum have been visualized through X-ray phase-contrast tomography.

Radiographic methods give critical information on structure and restoration, but previous exposure may alter other test results such as thermoluminescence dating. Other analyses are compromised by past history, storage or exhibition conditions, or previous treatment, whether objects have resided in collections for years or are recently acquired.

Techniques such as multispectral imaging reveal traces of color, underdrawing, residues, recarving, restoration, and other details not

apparent under normal lighting conditions. For example, traces of Egyptian blue are revealed when imaged using visible induced infrared luminescence (VIL) (Figure 2).

Organic pigments, binders, coatings, and adhesives may reflect ultraviolet radiation or may be stimulated to emit light when viewed under ultraviolet wavelengths of light (ultraviolet reflectance (UVR), or ultraviolet induced luminescence (UVL)), revealing traces of color or binders not visible to the human eye under normal lighting.

Computational photographic techniques such as reflectance transformation imaging (RTI) enhance surface details using a computer program to synthesize information gathered from multiple photographs of an object taken with the camera and subject in the same position while altering the angle of the light source at regular intervals. Such methods register and collate tiny variations in the reflectance of surface texture or topography, revealing original methods of manufacture, inscriptions, and other details not visible under normal conditions.



Figure 2 Sandstone head of Tutankhamen where broad stripes of Egyptian blue appear bright white when photographed using this technique. MFA11.1533.

Such techniques reveal new information about how objects were decorated. For example, Classical sculptures, once assumed to be unadorned, are today understood to have been highly colored with ornate decorative schemes.

Some museums and university collection conservators work alongside conservation scientists, who apply analytical techniques to answer questions about material components, burial accretions, and residues, and characterize evidence of past treatment or repair. These identifications help provide an understanding of the original materials, their history, and their current condition, in addition to providing clues to burial context.

Documentation

The process of examination is documented visually, through photography, and detailed in writing, as are treatment procedures and recommendations for display, storage, and future care. Proposals are produced in writing for the curator and discussed, and agreement is reached prior to any treatment of artifacts. These procedures are outlined in professional codes of conduct such as the Code of Ethics and Guidelines for Practice of the American Institute for Conservation of Historic and Artistic Works (AIC 2018).

Preventive conservation

Preventive conservation occupies significant resources and attention in the museum laboratory. Conservators understand the nature of materials in museum collections and how they respond to agents of deterioration such as light, extremes of temperature, relative humidity, and pollutants. They identify conditions that may result in instability or damage—such as soluble salts from burial, or active corrosion—and work to provide storage or exhibition conditions that will slow deterioration. Conservators and scientists study construction, padding, mounting, and packing materials which may interact with artifact materials, producing harmful changes

in the condition and chemical structure of objects.

Conservators work with exhibit designers, preparators, and collection care specialists to ensure that stable materials will be in proximity to objects installed in exhibit cases. Fabrics, support or mount surfaces, inks used on labels, support films for graphics, even the coverings used on lighting cables are all tested to identify potential sources of acid, sulfur, or other substances that interact with object materials. Packing methods and materials are similarly examined.

Conservation treatment

Objects undergo conservation treatment for a number of reasons. First, and most importantly, objects are treated in order to correct physically or chemically unstable conditions, including active corrosion of metals, flaking polychromy, waterlogged wood, powdering stone or ceramics, or damage from soluble salts in stone or ceramics (Figure 3).

Objects are also treated to reveal details or inscriptions important in understanding the object, including reduction of corrosion products or burial encrustations, while preserving information within these residues. They may also be treated for aesthetic reasons, to restore an appearance, aligning with current knowledge. Such restoration is carried out using stable, reversible materials which are easily removed should future interpretation change. By contrast, irreversible techniques like electrolytic reduction of corrosion products are today only sparingly used.

Staffing

Conservation laboratories are staffed with professional conservators with varied expertise. In Europe and elsewhere, often training focuses on the development of expertise in particular materials, for example: stone; glass, and ceramics; wooden artifacts; and wall paintings. In the United States, training generally focuses on the following disciplines: objects and sculpture; paintings; furniture and frames; textiles; prints,



Figure 3 Consolidation (strengthening) of powdering Nubian sandstone with methyl-trimethoxy-silane, a compound that bonds directly with silicon in the stone, forming a three-dimensional network. Source: Photography © Museum of Fine Arts, Boston.

drawings, and photographs. Conservators may have expertise dictated by the nature of the collections and, in some museums (for example, the Kelsey Museum at the University of Michigan), concentrate only on archaeological and ethnographic collections. In such cases, conservators are integrated into active and ongoing archaeology education and field excavations.

Conservation training

Today, most conservators hold graduate degrees from recognized training programs, and many are professional members of the AIC or other professional conservation organizations worldwide. Their training encompasses art history and archaeology, chemistry and physics, materials science, studio art techniques, ethics, risk assessment, and conservation methods, including treatment and preventive techniques. Candidates

for graduate training programs in conservation spend several years in pre-program internships or training positions before embarking on the application process. Some training programs focus on this area of conservation. An understanding of the interests and needs of the archaeologist in the field and the curator in the museum collection is critical to the handling, examination, analysis, storage, and restoration of artifacts. Field experience helps greatly to align the priorities of conservators, archaeologists, and future generations of stakeholders.

SEE ALSO: Computed Tomography; Conservation; Conservation Documentation; Conservation of Polychrome Natural and Architectural Surfaces; Conservation of Waterlogged Materials; Conservation Science; Ethics in Conservation; Imaging; Interpretation; Optically Stimulated Luminescence;

Photoluminescence of Egyptian Blue;
Reflectance Transformation Imaging (RTI) in
Conservation; Thermoluminescence; X-Ray
Tomography

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Conservation of Bone, Horn, and Ivory

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Animal remains are among the most prolific of archaeological finds and provide evidence of environmental conditions and diverse human activities (see ZOOARCHAEOLOGY). Animal soft tissue, including skin, muscles, and the internal organs, normally only survives in conditions where biodeterioration has been prevented by environmental factors (freezing or desiccation) or by the presence of preserving chemicals (tanned leather, embalming or bog bodies). In most archaeological contexts it is only the hard tissues, such as bone and teeth, that survive to be recovered (see TAPHONOMY). These hard tissues are biocomposites of a structural protein stiffened with a mineral, generally a form of calcium hydroxyapatite called bioapatite. They fall into two groups: osseous tissues, such as bone, antler, and teeth, formed from the protein collagen and highly mineralized; and keratinous tissues, such as horn, hoof, baleen (whalebone), and tortoise-shell, formed from the protein keratin and having a very much smaller mineral content. All these materials were used widely in the production of cultural objects after various degrees of work on them (see BONES AND IVORY). Whole small teeth, for instance, were used as amulets or sewn onto garments through the simple addition of a single perforation. The large tusks of animals such as mammoth, elephant, hippopotamus, walrus, and sperm whale were usually more heavily worked on, to remove the outer rind (cementum) and any traces of enamel, so as to reveal the easily carved dentine of the tooth, known as ivory. In order to understand conservation procedures for osseous and keratinous materials, it is essential to understand the degraded states in which they may be encountered.

Horn and other keratinous tissues rarely survive, because proteins are liable to chemical breakdown in alkaline (high pH) burial conditions and are also highly susceptible to biodeterioration by microorganisms in almost any situation where moisture is available (O'Connor, Solazzo, and Collins 2014; see DETERIORATION). Their recovery is unusual even in waterlogged sites—except in peat bogs, which provide anoxic, acidic (low pH) conditions and contain plant-derived biocidal compounds that inhibit biodeterioration. When the protein in bone or ivory is lost, there is nothing to hold the mineral component together and, even if bone is recovered from an excavation, when it dries out it can crumble into small fragments. The mineral component of these hard tissues is susceptible to dissolution in acid conditions. This loss of mineral is least serious for the survival of keratinous tissues, where it is present in very small amounts, but can be devastating for osseous tissues. As the mineral is stripped out, tissue loses its stiffness and collapses. The bone and antler recovered from the highly acid contexts at the Mesolithic site of Star Carr in Yorkshire, England were black, flattened, and flexible and had a fibrous texture resembling decayed leather (High et al. 2015).

As both acid and alkaline conditions can destroy osseous tissue, it may seem surprising that so much of it survives burial. This is due to the intimate way in which the protein and the mineral are combined. The collagen matrix protects the bioapatite from acid attack, while the bioapatite protects the most vulnerable parts of the collagen from alkaline attack and from biodeterioration by microorganisms (Collins et al. 2002). The result is that bone, antler, and ivory are surprisingly stable, except in extremes of pH. Even so, while these materials may remain recognizable and relatively robust, staining, cracking, an increase in porosity, surface erosion, and the addition of chemical contaminants may all occur, affecting the conservation requirements and information potential of the material. Water movement is critical. The rate of deterioration

of bone, for instance, is greatest in free-draining deposits in areas of high rainfall, as the water percolating through the bone will have a naturally low mineral content and a high oxygen content, promoting dissolution and biodeterioration respectively (see *DETERIORATION*). The best preserved bone—meaning bone with little alteration in porosity, largely intact collagen matrix, and minimal dissolution or replacement of bioapatite—can therefore be found in sediments that are anoxic and have little or no water movement, such as consistently waterlogged fine silts. Extremes of preservation can sometimes be seen within a single bone where the burial environment changes, as in the mammoth long bones from Lynford in Norfolk, England, which were submerged partly in silts and partly in layers of river gravel (O'Connor and Larkin 2012).

Arid sites present a different challenge. Groundwater movement is predominantly from depth to the surface, so buried bone experiences periodic wetting by water that is rich in dissolved minerals, in alternation with periods of drying during which those minerals can precipitate or crystallize within the bone structure. This causes dimensional stresses that manifest themselves as extensive fracturing, made worse by the loss of resilience as the collagen matrix is rapidly lost.

The deterioration of these biomaterials is also determined by their structure. Osseous tissues can be vascular, having an integrated blood supply, or nonvascular. Bone and antler are vascular tissues, and it is the organization of the blood vessels and the bone matrix around them that largely determine the patterns of deterioration. Long bones have a longitudinal grain and are often distinctly layered, so loss of collagen can lead to longitudinal splits and exfoliation of the surface layers. Antler is a disposable form of fast-growing bone that is laid down and shed annually. Like long bone, it has a longitudinal grain but the structure of the compact tissue is more chaotic in antler, so it does not form conspicuous layers and the cracks that appear are rarely straight. The degree of the mineralization that has occurred is also important, hence immature bone and antler, which are not so highly mineralized, are often less well preserved than mature bone from the same context.

The blood supply to teeth is entirely within the soft pulp tissue at the core of the tooth. The dentine is built up over the surface of the pulp in successive fine layers. Microscopic dentinal tubules pass through these layers, facilitating the movement of fluids throughout the tooth during life. Postmortem deterioration of dentine is predominantly expressed as radial and concentric cracking. When observed through a hand lens, these cracking patterns and the fine lamellar, nonvascular structure enable the worked ivory to be distinguished from bone. Dentine is also more highly mineralized than bone, and teeth with a protective cap of enamel can persist in graves long after the skeletal bone has completely deteriorated. However, ivory is much more susceptible than bone to significant dimensional changes if the water content of the collagen varies; so, as freshly excavated ivory dries in the air, shrinkage can open cracks and cause warping.

The precise details of the cracking, together with features in the dentine such as banding or patterns produced by the organization of the dentinal tubules, allow ivory of different species to be identified (Penniman 1952; O'Connor 1987). Elephant ivory, for instance, is formed from nested, oval cones of dentine and is very susceptible to splitting between these layers, producing characteristically shaped concentric cracking in transverse tusk sections.

The keratinous tissues are resinous-looking, tough, more or less flexible thermo-softening materials. In their raw state, horns, hoofs, baleen sheets, and turtle carapace scales (tortoiseshell) are distinctly different in shape, color, reflectance, translucency, and patterning; but both work and decay can greatly alter these attributes, making identification particularly problematic. Where they do survive wet burial, they are generally very fragile, matt, opaque, and dark brown or black, unless they are stained by metal corrosion. Fortunately these materials are all structurally different, and the visibility of their structures can be enhanced by decay (O'Connor, Solazzo, and Collins 2014). Cattle horn, for instance, develops over a bony horn core from skin keratinized layer by layer. As the horn tissue is dead, there are no blood vessels or nerves in this material; but, examined under low magnification, the cross-section is clearly made of finely

corrugated layers. On the surface, these corrugations appear as regular longitudinal ridges that are very distinctive of cattle horn. As the horn deteriorates further, these layers take on the appearance of longitudinally aligned fibres and finally disintegrate.

Many other factors can affect the state of preservation of hard tissues, for instance cooking or other processing designed to convert the raw material into an artifact. Material exposed on the surface before incorporation into sediments will be in poorer condition than material directly buried in rubbish pits or graves and, in the case of keratinous material, may not survive at all. Damage through trampling, abrasion, or gnawing of osseous material may be seen along with signs of weathering such as erosion, cracking, or flaking, which may be concentrated on particular surfaces where the material lay exposed and undisturbed (see TAPHONOMY). Bone grave goods may appear to be very much better preserved than the skeleton in the grave. The immediate environment of the skeleton will have been modified by the mass of rotting soft tissue and the vascularization of the skeletal bone will have provided a pathway for the spread of gut microbes during putrefaction. These organisms attack the bone from the inside, increasing its porosity and the potential for chemical dissolution over time. It is often observed that bone in the core of the body and closest to the gut is in poorest condition.

The most common form in which evidence of keratinous tissues survives is as mineral preserved organic (MPO) remains, where they have become infused with metal corrosion products (Janaway and Scott 1989). MPOs may go unrecognized on site, only becoming apparent during conservation. Solutions from corroding metal such as iron seep out into the surrounding sediments, where they react to form a solid crust around the original object. Organic materials directly adjacent to the surface of the metal can become incorporated in this crust, which forms a persistent mold or cast of the material's macrostructure and traps chemical traces of the organic material. How extensive and detailed these remains are is a function of the rate of decay of the organic material and of the speed with which the metal corrodes. Preservation can be further enhanced if the corrosion solutions are biocidal, as this will

inhibit biodeterioration. Traces of horn handles are frequently found on iron knives and swords, but in this decayed fibrous state many are mistaken for wood (O'Connor, Solazzo, and Collins 2014). Better preserved horn is mostly found in conjunction with bronze, brass, and debased gold and silver objects, as the corroding copper in these alloys forms a very effective biocidal solution.

The core aim of conservation is the preservation of information, and this can be challenging when we are dealing with animal hard tissues, because they can embody such a wide range of information (see ZOOARCHAEOLOGY). The most crucial time for these materials is the period during which they are uncovered. Uncontrolled drying in direct sunlight or exposure to repeated freezing and thawing or wetting and drying can lead to surface-detail loss, fragmentation, or complete destruction. If spreads of bone debris or assemblages of artifacts cannot immediately be lifted from site, a covering can be used to protect them from direct sunlight and frost damage or to maintain moisture levels and thus prevent soluble salts damage by minimizing the recrystallization of minerals within the bone.

The recovery of bone and ivory is discussed by O'Connor and Larkin (2012). Most osseous finds are relatively small and robust, and can be lifted from site by hand or by inserting a ridged board beneath them, to support them more evenly. If objects need extra support, as do skulls filled with sediment, crushed objects, or objects that can no longer support their own weight, they are often lifted in a plaster jacket that provides close-fitting external support. Direct strengthening of the objects themselves by resin consolidation before lifting is less desirable. Although it can help retain the object's structural integrity and surface detail, resin impregnation can also compromise its potential for radiocarbon dating or biomolecular analysis. Sediment inevitably becomes stuck to the surface of the bone, and removing this sediment and adjusting the position of misaligned fragments will require additional conservation work at a later stage. If the use of consolidants cannot be avoided, the material may need to be sampled prior to consolidation. Forward planning and liaising between all the specialists is crucial and conservation advice must be sought in order to determine the most appropriate

consolidant, whether a solution or an emulsion should be used, the optimum concentration of the resin, and the method of application that is best in the given circumstances (Johnson 1994). For instance, in wet conditions a resin solution will not penetrate the material but will form a skin on the surface of objects, while emulsions may not set while the object remains wet. In both cases the object will not be consolidated and may collapse when it is lifted or during transportation. Inorganic minerals have been proposed as alternative consolidating agents but remain experimental (North, Balonis, and Kakoulli 2016).

Sediments are cleaned from excavated bone and ivory using water and soft brushes in good lighting conditions. Toothbrushes are too harsh and even when used on well-preserved bone can result in polishing of the surface. The material should not be soaked: the surface is wetted, holding it above the water by hand so that the conservator can be confident that the brushing is only removing sediment and not abrading the surface. Rewetting dry material can cause the collagen to swell and fracture so water usage is kept to a minimum. Bone which is quite soft upon excavation may well become harder and more robust as it slowly dries in the shade or laid out within a well-ventilated building. It may take some days for bone to dry to the state that it can be packed away. If the bone is colder to the touch than the ambient temperature it is probably because water is still evaporating from it and it should be left to dry for longer. Ivory is given special attention because it can crack and warp during drying and may continue to break up when stored in environments with varying temperature and relative humidity. Very slow drying and stable storage conditions are important, but if ivory shows any signs of damage as drying progresses the material will need to be consolidated. Reconstruction, gap-filling, and mounting of these materials are demonstrated by Larkin (2010).

Where keratinous materials survive it is essential to maintain as closely as possible the conditions that have preserved them, for example, waterlogged or desiccated, until they can be actively conserved. Wet materials are stored in closed containers in dark, refrigerated conditions to reduce the risk of accelerated biodeterioration while they await conservation.

Biocides such as dichlorophen or disodium ortho-phenylphenate are best avoided because of their toxicity and because they can cause chemical deterioration of the degraded material. Wet storage is only a temporary measure and growth of fungi and other organisms can be prevented by refrigerated, dark storage. Ultimately the material needs to be both stable and dry. "Dry" does not mean "desiccated": the material should be dry enough not to lose further water at the ambient relative humidity of the store, and not desiccated below that ambient humidity. Air drying can cause shrinkage and patterns of break-up that reflect the structure of the material. For example, horn may warp and exfoliate as free water is lost, becoming hard and brittle. Once dry it can slowly continue to lose water held within the decayed protein, opening cracks and increasing fragility. Consolidation combined with controlled drying or freeze-drying techniques have been used to overcome many of these problems (Kaye, Cole-Hamilton, and Morphet 2013).

Bone will always contain a proportion of moisture but this will vary with the relative humidity in the air around it so it is liable to "sweat" if it is sealed in plastic containers and temperatures in the storage area fall. Such condensation can promote mould growth so bone should be held in open-topped or perforated bags within acid-free card boxes that allow a slow exchange of air with the storage environment. A thin polythene foam sheet cut to the size of the bag and inserted behind an object can provide a standard level of physical protection for worked osseous objects but fragile objects may need to be housed in padded boxes. Longer-term passive conservation of conserved bone, ivory and horn is essentially all about good short-term treatment and packing followed by long-term stability of curation conditions.

SEE ALSO: Conservation; Conservation Science

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Conservation of Earthen Building Materials

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Introduction

Earth (clay-rich soil) has been used as a building material since antiquity and throughout the history of humankind, though only recently has earthen architecture become scientifically accepted as a discipline of its own. Earthen architecture has been present in the five continents and reveals a wide range of cultural diversity of expressions, forms, techniques, and building styles through its historical heritage. Currently, there are still 15–17 percent of people living in earthen settlements (Correia 2016).

In recent decades, more interest, focus, and research have been given to the conservation of earthen heritage. World Heritage plays an important role in increasing worldwide interest, especially considering the outstanding value of some of the earthen sites that are at great risk. Creation of the *UNESCO World Heritage Earthen Architecture Program (WHEAP)* was meant to disseminate the international significance of this exceptional and fragile heritage. The survival of this heritage is a challenge that needs to be addressed with thoughtfulness, knowledge, and humbleness.

There are several publications on earthen architecture conservation. Most address the conservation of individual sites, and very few publications compare the different intervention approaches (Warren 1999; Matero and Cancino 2000; Mileto and Vegas 2014; Gandreau and Sadozai 2014; Correia, Guerrero, and Crosby

2015; Correia 2016). Consequently, this fact limits, in a way, the opportunity to establish critical reflections on the level of success and to apply the obtained results in present and future actions (Guerrero, Correia, and Guillaud 2012).

Unfortunately, there are great difficulties conserving earthen structures and preventing their decay. Several reasons for this can be identified: inadequate and inefficient intervention, lack of follow-up and maintenance, lack of preparation of the team members, incorrect intervention interpretation, and lack of material knowledge.

Failure of the physical condition of the structures may result from lack of action or discontinuation of conservation measures and conservation practice. However, as earth is such a fragile material, inaction to protect and conserve, in some instances, can endanger the timely preservation of the last remains. As defended by Cesar Brandi, sometimes the site can be beyond recovery, if the unity principle addressing the archaeological remains as a whole is not present anymore (Correia and Fernandes 2006).

Recurrent failure can also occur due to the use of incompatible materials and methods applied by professionals without enough specific knowledge or experience in earthen heritage conservation. More accurate testing and assessment is required before the use of new treatments and stabilization materials.

Universal solutions are also sometimes employed, using only one intervention approach. The problem might lie in the lack of research and knowledge of the material compatibility, its reversibility, and long-term impact. A clear understanding of earthen architecture, different earthen building styles, integration of local knowledge and skill, identification of seismic performance, differences of behavior regarding new intervention, a critical view of different intervention approaches, and their impact on the earthen fabric are required to encourage a change towards the conservation of this fragile heritage (Correia 2016).

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This is why a comprehensive knowledge of the different technical strategies of conservation should be documented and further critically assessed, before an informed decision can be made, as each case is unique. Different technical strategies can be considered, such as preventive measures, modification of the earth mixture, use of consolidants, and structural reinforcement.

Preventive measures

One measure that in general guarantees safe conservation of earthen heritage is *reburial of the excavated structures*. Although this is an extremely drastic strategy with strong implications for the site value and accessibility, it provides priority to its comprehensive preservation in the long term. However, the procedures to rebury remains that have already been excavated, exposed, and documented should be extremely cautious, as once the site is reburied, it would be difficult to monitor the original remains. That is why, for the protection of very damaged earthen archaeological structures, the use of membranes

such as geotextiles is recommended, which have the quality of physical barriers that allow the natural flow of water through the soil and the archaeological remains.

A less radical measure is the designing and placement of *protective shelters*. This measure has been proven effective for several decades in some cases, and ineffective in others due to wind dynamics. It has the advantage of favoring public visit to the sites, while protecting the site from possible damage caused by rain, wind, snow, or hail. However, any change in the temperature and humidity of the earthen structures sets their material integrity at risk, as much of their stability is derived from the equilibrium they possess with the amount of water they contain. An excessively humid earthen structure can disintegrate, but the same happens if the earthen structure is too dry, as it loses cohesion. As a result, when choosing shelters to cover earthen sites, the main aim should be the hygrothermal balance of the interior spaces. Shelters can also dramatically alter the visual relation of the archaeological sites. Therefore, their form, height, and materials must be carefully and sensibly designed (Figure 1).



Figure 1 Chan Chan is an earthen endangered archaeological site classified as World Heritage, in Trujillo, Peru.

Source: Photo by Mariana Correia, January 2017.



Figure 2 Arg-e Bam is an earthen citadel classified as World Heritage, in Bam, Iran.
Source: Photo by Mariana Correia, October 2011.

The structures exposed to the elements, and those protected by shelters, will require a preventive conservation intervention, involving a direct physical intervention, as, for example, the application of a *surface coating*. For a more balanced approach, it is indispensable to consider the hygrothermal requirements needed for earthen structures. This will protect the earthen structures from possible surface damage, without impeaching the natural permeability of the building components. Among the most frequently used technical strategies is the use of capping on the top of the walls (e.g., thatch), especially on walls that have lost their integrity. Also common is the use of sacrificial coatings on the top of the walls, and earthen renders on the vertical exposed surfaces.

For an adequate wall adhesion, these coatings are often made with an earth mixture like the original fabric, with the possibility of subsequent removal, as the reversibility principle should be considered. Sacrificial coatings generally have a higher amount of gravel or other aggregates, which improves erosion control and site stabilization. The surface coating should not be more rigid and impermeable than the original earthen fabric that needs to be protected, and it should

receive regular maintenance. In earthen heritage, conservation should be part of a continuous preventive activity.

The use of geotextile membranes to protect the earthen structure before applying the surface coating can also be considered. These are often used on the reburial of excavated structures, as previously mentioned. They are useful because once covered with sacrificial coatings, they allow the natural flow of water vapor in the structures, generate a surface protection barrier, and can be removed when required. However, the membrane selection and application and its earthen coating should be addressed carefully. It often happens that, upon application, the elements and components of the site that were covered are no longer recognized, and the architectural value of the component is lost (Figure 2).

Modification of the earth material

Modified earthen materials usually create a more durable fabric. This can be achieved through stabilizers, additives, and adhesives that can turn the natural soil into a more effective earth

mixture. These materials can be organic or inorganic, of natural or synthetic origin. *Stabilizers* are materials that modify the physical and chemical characteristics of natural earth, increasing its resistance to mechanical stress, as well as to the effects of moisture (Correia et al. 2015). The most common stabilizer is lime, but fired gypsum has also been used for a long time to improve the earth mixture. The earthen material that forms the sacrificial coatings, as well as some components designed to fill gaps in the original building systems, are often stabilized. This process consists of the modification of the natural qualities of the earth to allow it to acquire a greater mechanical resistance, adhesion, water resistance, and porosity.

For decades, cement was used as a soil stabilizer, or as a surface coating when addressing earthen heritage intervention. It was believed that its use could avoid periodic maintenance and could provide a more effective response to harmful weathering agents. However, as it has been widely documented, cement is incompatible with earth, due to its relative difference in permeability, mechanical strength, and contraction–dilation coefficient. This difference generates dynamisms within the earthen structures that progressively degrade it. The impermeability of cement traps water vapor inside the earthen material, which ultimately leads to the destruction of the structure. Therefore, its use is not recommended, and extensive interventions have been planned to carefully remove the cement capping.

Additive is a general term for substances that do not interfere with the chemical reactions of clay, but which provide a physical activity that improves its properties. Sand is one of the additives most frequently applied to balance the expansive and detractive activity of argillaceous soils (Correia et al. 2015). Different additives can be used, such as pulverized fly ash (PFA) and natural additives such as egg white, cactus juice, straw, chaff, wood chippings, and animal hair.

Several different additives have survived as part of the intangible vernacular knowledge. This is the case, for instance, with mucilage, juices, and gums of vegetable origin, as well as some animal proteins, which offer greater consistency to the earth mixture and improve its adhesion. This also improves the water resistance of the material,

while maintaining the permeability of water vapor through the material. This is important because the earthen wall constantly balances air and humidity between the interior and exterior. A similar effect is achieved by adding small proportions of lime or gypsum to the earth mixture. These agents produce chemical reactions that with time provide a greater mechanical and water resistance to the earth mixture.

Adhesives are emulsions that bond soil particles together and are primarily valuable in attaching plasters to their substrates. The most common emulsions are acrylic emulsions, such as “copolymers of ethyl acrylate, methyl methacrylate, and/or ethyl methacrylate” (Oliver 2008). Some authors do not recommend the use of emulsions, due to their difficult penetration when there is an absorbent material, but also because they have no reliable additives in terms of material aging.

Use of consolidants

A consolidant is a material that is applied on surfaces to establish cohesion of the particles, thus providing greater protection against surface weathering. On earthen walls, *inorganic consolidants*—aqueous solutions and/or dispersions of different salts—are commonly employed. Once applied on surfaces, through the soil capillaries, they stabilize the clays and agglutinate them to smaller-size particles. This group includes substances used in traditional maintenance, such as limewater, potassium aluminum sulfate (alum), and alkaline silicates (sodium or potassium) (Correia 2016). They can be applied through spray or by paper and brush absorption.

There are also traditional materials, such as *natural organic consolidants*. This is the case with animal glue, gum, beeswax, egg white, casein, natural cactus juice, and so on. Each one has a different impact on the earthen surface. Some have a lower penetration than others, or can react with sensitivity to humidity. Others are more prone to biological attacks and can change color with time. Natural cactus juice is commonly used in Latin America, as it has a good balance between availability, price, and short-term impact, despite some experts arguing that for medium- and long-term impact it does not present enough positive outcomes.

Concerning the *synthetic organic consolidants*, several products have presented good results, as is the case with silica ester, ethyl silicate, polyvinyl alcohol (PVA), and polyvinyl acetate. One of the most popular products is ethyl silicate, due to its good penetration and longer lasting results maintaining the color and the wall's earthen fabric in good state. In Huaca de la Luca, Trujillo, Peru, it has been successfully used for over 20 years. However, its high cost restricts its use and sustainable application.

Silicone and synthetic resins are also frequently applied for surface protection. However, authors restrain their use for surface exterior treatment, as they tend to form a film on the surface and "with the exfoliation of this film and the detachment of the treated part, more damage is done to the surface to be protected than if it had not been treated at all" (Alva and Chiari 1995, 105).

Structural reinforcement

For the repair of damaged structures, *nonintrusive structural reinforcements* provide an option. When the damage to archaeological remains is so severe that their unity, load-bearing capacity, or survival are at risk, it becomes necessary to integrate systems of structural support. These systems must be carefully designed, so as not to alter the natural performance of earthen structures. Physical and chemical compatibility is essential in this case to achieve continuity in the transfer of mechanical stresses by filling-in missing parts. This is possible by applying mud grouts to fill-in cracks, or using bonding mortars to replace disintegrated earthen material. In the case of lacunas, the size of the gap should be considered to balance the structural filling. This does not mean that the original material must be replicated, as this could lead to the ethical dilemma of reconstruction and historical falsification. Unfortunately, this is a frequent choice in the case of earthen heritage, which is incorrectly chosen, as it is often considered by professionals that earthen reconstruction is acceptable in archaeological heritage, when it is not in other materials.

There are conditions in which the severity of the earthen archaeological remains guides the intervention design for radical adjustment

regarding its transfer of loads, which only becomes possible through *intrusive structural reinforcement*. Because of earthquakes, differential sinks, flooding, or similar agents, the relation between the structural components can be interrupted, so that it becomes necessary to incorporate components that bind them together again. The introduction of supports allows the components to separately acquire a new condition of structural stability as isolated units. In both cases, it is necessary to consider that the difference between the strength of the remains and the reinforcements must be the smallest possible to avoid these measures being more harmful than beneficial.

Structural reinforcements made of wood, bamboo, or vegetable fibers have been found to be compatible with earthen structures, since they have similar coefficients of strength and dilatation. However, it is important to take care of the transition points between these reinforcements and the remains, so that balanced stress distributions are developed, instead of load concentrations.

In case there is a need to use materials with greater resistance than wooden structures, stone, brick, and even steel components have been used. However, it is necessary to generate a gradual unloading process in transition areas, allowing a gradual passage from a highly resistant material to the earthen built material. Intrusive structural reinforcement should be the last option for intervention and not the first choice to consider, as the principle of minimum intervention is essential when addressing earthen heritage intervention.

Conclusions

The development of intervention procedures for the conservation of earthen built heritage should be flexible, enabling suitable solutions for each case. It is necessary to consider the individuality of each site and that the conditions of the different sites need to lead to specific solutions. This is why documentation and registration of the different results obtained during conservation actions are required, in order to have a critical assessment of their level of success or failure, according to the specific conditions in which they were developed.

When addressing the conservation of earthen structures, one of the most serious errors is the search for a “permanent” solution. The development of expensive works addressing incompatible materials, cement-based mortars, or structures of reinforced concrete has led to irreparable damage to earthen heritage.

History of earthen architecture reveals that its structures are closely related to the societies that have inhabited them and have continuously maintained them. Thus, the solution for the preservation of this heritage should be based on a proper design of management processes from different time frames, based on consistent procedures. These actions necessitate the participation of communities to which the heritage belongs; thus, within planning for the management of the sites, actions to recover traditional knowledge and the practical transfer of earthen technology are of great importance (Guerrero 2015). The integration of local intangible heritage is part of a site’s living traditions and preservation.

Lack of planning and strategies definition can involve reactive, instead of proactive, actions, which in the case of earthen architecture could have irreparable loss. A greater number of experts and conservation professionals with certified education on earthen heritage conservation would increase the quality standards and the expertise in the field.

For a balanced conservation approach addressing earthen archaeology, a comprehensive course of intervention needs to be established for each site, involving different stakeholders, an interdisciplinary expert team, and consideration of the different indicators of quality and of best practices.

SEE ALSO: Ancient Mortars and Plasters; Conservation; Cultural Resources Management; Deterioration of Earthen Building Materials; Polymers in Conservation; Preventive Conservation in Archaeological Sites

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Conservation of Fibrous Materials

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The class of organic fibrous artifacts includes a range of raw plant materials and construction technologies, including categories such as basketry, textiles, and paper. Though common among many past societies worldwide, the presence of fibrous artifacts in the archaeological record is rare due to their perishable nature. Preservation conditions limit organisms causing biodeterioration and offer protection from fluctuating environments that cause chemical and mechanical breakdown, such as repeated wetting–drying cycles. Most often, fibrous artifacts are recovered from anaerobic waterlogged sites, or from spaces that offer added protection within an arid environment, such as in a cave or sealed vessel. Typically, they are found in fragmentary and weakened degraded states, particularly when recovered from waterlogged sites. Their preservation may be due to chemical transformation, such as charring or mineralization, in which the form of each individual fiber is retained. Additionally, fibrous artifacts are often found in association with human remains, which can impact artifact preservation, and this adds additional ethical considerations to their study and conservation. The conservation of fibrous artifacts includes first-aid recovery in the field, examination, preventive conservation measures such as creating storage mounts, and treatments to clean and stabilize artifacts.

“First-aid” recovery

Significant damage can occur to fibrous artifacts during excavation and added caution is often needed. Fibrous artifacts may require “first-aid”

in the field during recovery to prevent rapid deterioration and damage. Block lifting is beneficial in either arid or waterlogged ground, wherein the surrounding earth is excavated and encapsulated along with the artifact (Jones et al. 2007). Subsequently, the artifact can be transported and carefully excavated by an expert such as a conservator working in a controlled environment. Artifacts recovered from a submersed environment should be kept damp and either chilled or frozen until controlled drying can be performed. Artifacts may require temporary consolidation or support during excavation without impacting future potential for carbon-14 dating, which can be accomplished using cyclododecane (Pohl et al. 2009). Care should be taken to minimize alterations to the artifact during excavation; folds and distortions should be left, and permanent measures such as consolidation with an adhesive are not advised.

Conservation study and examination

Initial conservation examination includes identifying materials and construction technology, as well as an assessment of condition and photo documentation. In-depth study of archaeological fibrous materials is often conducted by conservators because of their skillset and training, which can be useful to archaeologists in providing additional information on recovered artifacts. Fiber identification is important for understanding the artifact's context and degradation, and for determining optimum treatment. Natural raw materials derived from plants are cellulosic fibers, all of which have diagnostic features that make their identification possible, often to a genus or species level. When taxa are indeterminate, it is still beneficial to identify key features that categorize fibers, such as distinguishing between bast, leaf, and seed fibers of plants. Fiber identification is most often achieved using microscopy and comparative examples of known fiber types. Diagnostic technological information is also recorded, such as the fabrication structure (i.e.,

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the weave or looping structure of a textile), fiber processing technology (i.e., the twist and ply of yarn, or the splitting of basketry elements), design patterns, and surface decorations. If the surface is obscured by dirt or accretions, it may be necessary to first clean the artifact before a technological examination can take place.

Additional analysis using nondestructive or microdestructive means may be conducted to further identify materials such as residues and dyes, and to examine the extent of deterioration and effectiveness of conservation treatments. Analytical methods presently used in the research of fibrous artifacts include Fourier transform infrared spectroscopy, gas chromatography mass spectrometry, surface-enhanced Raman spectroscopy, X-ray fluorescence spectroscopy, and scanning electron microscopy (Brettell et al. 2017; Maccerrelli et al. 2016; Fischer 2009).

Preventative conservation

Because of their fragile and often fragmentary state, it is crucial to minimize handling and provide full support to fibrous artifacts while both stored and studied. Though the solutions may be simple, the impact of preventing further damage can be substantial. All permanent support mounts should be constructed with archival materials, provide ridged though often padded support, and allow the artifact to be visible without requiring handling to view. Supports may be as simple as a padded archival grade tray or box, though more fragile or awkwardly shaped items may require additional support and immobilization. A number of case studies demonstrate optimal strategies for designing appropriate storage for fibrous artifacts (Margariti and Loukopoulou 2016). Sink mounts have a custom-made padded cavity cut into the base where the artifact sits partially recessed, and can provide support and immobilize fragile artifacts. Also, textiles can be mounted in double-sided storage mounts which allows access to both sides while fully supporting the artifact as it is turned over.

Proven materials for constructing supports include archival grade box board, fluted polypropylene board, high- and low-density

polyethylene or polyolefin foam, cotton twill tape, washed cotton muslin and washed polyester organza, archival grade polyvinyl acetate adhesives, and archival grade low-melt hot glue. Acidic paper materials and unstable plastics should be avoided. Also, where possible, it is ideal to avoid materials that attract static electricity such as plastic bags; this can cause difficulty manipulating loose fiber fragments.

Controlling environmental conditions, including temperature, relative humidity (RH), and exposure to light, is an important step for preventative conservation of fibrous artifacts. Fibrous artifacts are ideally stored in the dark, at low to moderate temperatures, with stable mid-range RH. Light causes chemical breakdowns leading to discoloration, and higher temperatures increase rates of chemical reaction. A widely fluctuating RH causes mechanical breakdown as fibers shrink and swell in response. High levels of RH cause fibers to swell and lose strength, while very low RH embrittles fibers; this response can vary depending on the preexisting acclimation, material type, and the stresses on fibers within the artifact's construction. Additionally, the combination of high temperature and RH levels increases the risk of biological growth such as mold, and pest infestations. While pests may be problematic, preventive treatment using pesticides is not advised; infestations can be effectively managed by freezing artifacts, which can kill all stages of life of insect infestations when done appropriately.

Treatment

Cleaning and drying

Surface cleaning is often necessary to facilitate examination, identification, research, and storage of fibrous artifacts. It is also an important first test to treating a fibrous artifact, as surface dirt and accretions can be hygroscopic, absorbing and retaining moisture at the surface of the artifact, which is potentially damaging. Dry mechanical cleaning is the least invasive and most common form of cleaning; dirt is lifted with a small fan brush, working towards a vacuum nozzle which clears the lifted dirt. The nozzle should be covered with a fine mesh fabric and held at a distance to

prevent uptaking fibers from the artifact itself. In many instances, this is the only cleaning measure required.

Aqueous cleaning is more invasive and a higher risk treatment, and though common for desiccated artifacts in past decades, it is used less often today. Fibers swell and regain flexibility as they absorb water, which severely reduces mechanical strength and may lead to fiber collapse. Aqueous cleaning can also cause colorant bleeding or fading, and loss of important residues. Localized aqueous cleaning may be more appropriate to address unwanted staining, such as using chelating agents to remove iron staining.

Fibers shrink as water evaporates during the drying phase, with potential to permanently distort the artifact. When aqueous cleaning is performed, drying must be gradual to minimize damage. This is achieved by replacing water with solvent in intervals, or freezing wet artifacts to sublimate ice under vacuum (Brooks and Eastop 2011). Similar drying processes are also used on waterlogged artifacts (Senge and Carrlee 2013).

Reshaping

Aqueous methods of flattening and blocking archaeological textiles were once common, though this practice has fallen out of trend. Original creases provide information about how the object was used or buried. While archaeological textiles are routinely unfolded, in many instances the creases and folds are maintained. When artifacts are so distorted that reading the artifact is inhibited, it may be appropriate to relax creases and folds, and reshape the artifact using humidification. This process can be conducted locally or in a humidification chamber using water and/or alcohol vapor for reshaping both flat textiles and three-dimensional fibrous artifacts. Humidification has reduced risks compared to aqueous submersion; however, water vapor causes fibers to swell and increases the potential for biological growth. Alcohol vapor can help fibers regain flexibility without causing swelling and is also a biocide. Once flexibility is regained, artifacts can be coaxed closer to their original

shape. Supports are used to hold the position during drying, which the fibers retain once dry.

Stabilization treatments

Commonly, stabilization of fibrous artifacts requires additional supporting material for strength and overall coherence. These treatments vary based on the needs of individual artifacts and are ideally carried out using methods and materials that allow for future reversal or retreatment. Small localized mends using stitching, ties, or small amounts of adhesive can help regain the integrity of the artifact's structure in areas of partial loss. This can be achieved with minimally and strategically placed mends such as with hair, silk, or nylon filament, long fiber archival paper, or a compatible adhesive. Flat artifacts can be attached to a backing using stitching or specialized adhesives; however, in doing so, one side of the textile is made inaccessible. Consolidation treatments can be carried out on highly fragile objects that are too fragile for basic handling. Because consolidants absorb into the surface, these treatments are essentially irreversible. For waterlogged artifacts, it is necessary to permanently replace water molecules to prevent fibers from collapsing; this has been achieved with polyethylene glycol.

Conclusion

In many instances, a minimal approach is often the smartest and more effective for long-term preservation. Often, poorly executed treatments or treatments using incompatible materials will cause damage to an artifact over time. Before adding a material or adhesive to an artifact, it is necessary to understand the compatibility and long-term effects of the materials. The addition of adhesives, consolidants, and impregnation materials can become problematic for future study and analysis, including DNA analysis and carbon-14 dating. These considerations must be weighed along with the immediate stabilization needs and the artifact when selecting an appropriate conservation treatment.

SEE ALSO: Chromatographic Techniques in Conservation; Deterioration of Waterlogged

Materials; Electron Microscopy in Conservation;
Raman Spectroscopy in Conservation

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Conservation of Metals

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Introduction

History of archaeological conservation

Archaeologists and chemists were the first professionals to carry out the conservation of archaeological artifacts, which led to the growth of “conservation” as a profession and to the establishment of the “conservator” as a professional who practices conservation of heritage materials. Large industrial metal objects have become part of our archaeological heritage; the preservation of spacecraft and ships is becoming increasingly prominent. Training to be a conservator of archaeological metals involves education in metallurgy, metalworking and manufacturing techniques, metal corrosion, archaeology, art history, analytical methods, and the ethics of conservation.

Corrosion

The greatest challenge presented by metals when it comes to their preservation is their instability and their tendency to revert to the original ores used in their manufacture, through a process called corrosion. Corrosion is largely an electrochemical process involving water and oxygen. Other forms of deterioration include physical damage such as cracking, delamination, and the influence of biological organisms. The preponderance of corrosion and other forms of deterioration depends on the composition of the metal, the method of manufacture and metalworking techniques, the life of the object prior to burial, the burial environment, the environmental conditions after excavation, and the handling and conservation treatments after excavation.

Copper and copper alloys in land burials corrode by forming carbonate, oxide, and chloride compounds sometimes accompanied by calcareous or siliceous encrustations (Cronyn 1990). Copper sulfides are often caused by sulfate-reducing bacteria in anaerobic conditions. Copper sulfide and copper chloride corrosion products are commonly found on marine copper and copper alloys. The copper iron sulfide, chalcopyrite, can form on bronze from sulfate-reducing bacteria, in anaerobic burial conditions. For copper alloys, removal or stabilization of chlorides is the main challenge; with marine objects, this challenge is complicated by marine concretions.

Iron and steel are sensitive to chloride contamination that can accelerate and perpetuate corrosion. Bacteria can contribute to the corrosion of iron and steel: sheath-forming bacteria can cause corrosion through differential aeration, and sulfate-reducing bacteria attack in anaerobic burial conditions, forming black iron sulfide. Iron in seawater forms iron hydroxides, iron chlorides, iron sulfide, and iron oxides (Pearson 1987).

Archaeological silver tends to form stable corrosion products: silver sulfide and silver chloride. Silver sulfide forms on silver from sulfate-reducing bacteria in anaerobic conditions; in aerobic conditions, silver chloride forms. Lead forms lead carbonate, lead oxides, lead chloride, and lead sulfate in aerobic conditions and lead sulfide in anaerobic conditions. These are all considered stable corrosion products that do not contribute to continuing corrosion, although they can hinder legibility. Tin is most commonly found as an alloy in bronze or pewter and forms two types of oxidation products. The formation of lead sulfate on pewter can protect it from further corrosion on the seabed. Gold, as a noble metal, does not corrode unless alloyed with baser metals such as silver or copper. Aluminum alloys are protected by the formation of Al_2O_3 but can be attacked by chlorides if this protective layer fails (Watkinson 2010).

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Composite and decorated objects

Composite objects present particular challenges, such as the treatment of waterlogged wooden ships with polyethylene glycol (PEG), which corrodes the iron components. Several forms of decoration on metal artifacts that involve different metals in contact with one another—such as niello, damascening, gilding, and enameling—can present individual challenges for their conservation.

Ethics

Among those international charters dealing with the ethics of preservation of the archaeological heritage, the 1990 ICOMOS Charter for the Protection and Management of the Archaeological Heritage and the 2001 UNESCO Convention on the Protection of the Underwater Cultural Heritage are prominent. The Metals Working Group of the International Council for Museums Committee for Conservation (ICOM-CC) publishes periodic conference proceedings. The trend in conservation has increasingly favored minimal intervention and alteration of the original object, reversibility of conservation materials and methods, and nondestructive methods of investigation and analysis.

Approaches to conservation

It is the shared responsibility of the archaeologist and the conservator to collaborate in decisions regarding the excavation and preservation of archaeological objects. The options to consider include removal from the burial site through excavation and lifting, preservation in situ, and reburial (Watkinson and Neal 2001). Conservation can be carried out in situ as a first-aid measure for removing delicate or difficult objects or as a means of long-term preservation. Proper handling and packing immediately after excavation is vital for minimizing the shock of removal from the burial equilibrium and exposure to dissimilar conditions of temperature, moisture, and oxygen. Once an object is brought to the conservation laboratory, two basic approaches to conservation treatment can be taken: interventive (active) or preventive (passive). Interventive

conservation implies the direct application of conservation materials for the treatment of the object. Preventive conservation involves controlling the environment that surrounds the object either to stabilize it temporarily, until interventive treatment can be carried out, or as a permanent stabilization strategy.

Research and investigation

Research to be carried out before conservation treatment begins includes the identification of the metal and alloys, corrosion products, and causes of corrosion and the technology used to manufacture the metal object. With all metals it is important to ascertain the condition of the object before deciding on a conservation treatment (Cronyn 1990). Numerous analytical techniques are available for examining the morphology, elemental composition, and crystalline structure of corrosion (Dillmann et al. 2013). Electrochemical methods may be used to analyze the surface of metal in conjunction with time-lapse synchrotron X-rays (SR-X-rays). Voltammetry of microparticles (VMP) is an electrochemical technique for the identification of metals and corrosion products and for mapping corrosion products on the artifact. Laser-induced breakdown spectroscopy (LIBS) is useful as a nondestructive method for the elemental analysis and depth profiling of archaeological metals. Radiography using X-radiography and 2D or 3D X-ray computer tomography of metal objects prior to cleaning can reveal considerable information, including the extent of mineralization, the location of the original surface, decorative elements, and evidence of manufacture. Documentation of all research, investigation, and treatment is a necessary part of the conservation process for which databases are used.

Stabilization

The term *stabilization* is used to denote the retardation of deterioration with the goal of halting deterioration by any number of interventive or preventive conservation means. By mitigating the physical, chemical, and biological factors of deterioration, the conservator attempts to achieve stabilization.

Interventive conservation

There are numerous interventive means by which one can stabilize and conserve corroding metal artifacts. Those considered here are cleaning, chloride conversion, chloride removal (desalination), corrosion inhibitors, and protective coatings.

Cleaning

The cleaning of metal artifacts may be carried out by mechanical and/or chemical means. Initial cleaning involves investigative work to ascertain the extent and location of corrosion, the location of the original surface and surface detail, and the physical condition of the object.

Mechanical cleaning Mechanical cleaning is carried out with small hand tools such as scalpels, vibrotools, cavitrons, glass bristle brushes, and grinding tools using illuminated magnification. Air-abrasive techniques using glass bead microspheres, walnut shells, sodium bicarbonate, and aluminum oxide are sometimes used to clean metals. Laser cleaning with carbon dioxide lasers, Nd:YAG (neodymium-doped yttrium aluminum garnet) lasers, and excimer lasers and TEA-CO₂ (transversely excited atmosphere carbon dioxide) laser ablation have been applied to archaeological metals. Ultrasonic cavitation can enhance chemical cleaning by dislodging residues when used with caution.

Chemical cleaning Acids, alkalis, complexing agents, and chelating/sequestering agents are used to clean archaeological metals. Inhibitors and surfactants may be added to promote cleaning. The removal of residual chemicals must be carried out following cleaning.

The cleaning agents for calcareous encrustations and corrosion on copper and copper alloys include alkaline Rochelle salt (50 g/l sodium hydroxide and 150 g/l sodium potassium tartrate), alkaline glycerol (150 g/l sodium hydroxide and 40 ml/l glycerol), citric acid (sometimes buffered with ammonium hydroxide or thiourea), Calgon (150 g/l), formic acid, sulfuric acid, sodium hydroxide, ammonium hydroxide, ammonium tricitrate, ethylene

diamine tetra-acetic acid (EDTA) (disodium or tetrasodium salt), sodium diethylene triaminepentaacetic acid (DTPA), and sodium tripolyphosphate (Scott 2002). The trend from the twentieth century to the present day involves the gradual abandonment of “stripping” metals of corrosion in favor of retaining the patina whenever possible.

Ethylene diamine tetra-acetic acid (EDTA: disodium salt) and weak acid solutions will remove lead carbonate from lead objects. Ion-exchange resin has been found useful for the removal of lead chloride and carbonate from lead and pewter objects. Tin coatings on copper alloys require mechanical cleaning, as they are susceptible to alkalis and acids.

Conversion of chlorides

In the majority of cases the conversion or removal of chlorides is necessary to prevent further corrosion of copper, copper alloys, and iron. Conversion coatings interact with the corrosion to form stable corrosion, as in the application of sodium sesquicarbonate to cuprous chloride to form the stable cuprite (copper oxide), which can also generate undesirable corrosion products.

Desalination

The process of removing chlorides from a metal artifact through immersion or with poultices is called desalination. The removal of chlorides may be carried out through one out of several methods, and the release of chlorides can be monitored.

Water washing The solvation and solubility of chlorides varies; iron chlorides tend to be more soluble than other chlorides, such as copper chloride and silver chloride. Removal of chlorides during immersion in water has been improved through the introduction of alkaline substances.

Alkaline washing Alkaline solutions that increase the solvation and removal of chlorides while acting as corrosion inhibitors are especially useful for iron, preventing further corrosion (Watkinson 2010). Sodium hydroxide is typically used for this purpose.

Subcritical high-pressure alkali treatment

Stabilization in subcritical fluids with 0.5 percent (w/w) sodium hydroxide solution at 180 °C was found to be faster than with a 0.5–1.0 percent sodium hydroxide solution (with or without cathodic polarization) for removing chloride from marine iron, as in the case of the American Civil War *Hunley* submarine (Dillmann et al. 2013).

Complexing agents

Aqueous ethylene diamine solutions (5% v/v and 11.5 pH) have been used to extract chlorides from iron with reportedly less success than aqueous solutions of sodium hydroxide (2%). Aqueous acetonitrile complexing reagent has found use for the removal of chlorides from marine bronze, although it can disrupt the cuprite layer.

Chemical reduction

The aqueous extraction of chlorides from land and marine iron has been greatly improved with the alkaline sulfite reduction method since the 1970s. This method involves immersing the iron object in a solution of sodium hydroxide and sodium sulfite of varying concentrations, at temperatures ranging from 50° to 70°C (Scott and Eggert 2009).

The alkaline dithionite (40 g/l sodium hydroxide and 50 g/l sodium dithionite) reduction method was originally devised for bronze from saltwater sites but can also be used on bronze from land sites.

Electrolytic reduction

Electrolytic reduction involves making the object to be cleaned the cathode, which is immersed, with an anode, in an electrolyte to which an external electric current is applied. The electrolytic reduction of copper alloy objects using an externally applied current through a sodium hydroxide, sodium carbonate, or sodium sesquicarbonate electrolyte will alter or remove the patina. Using distilled water as the electrolyte and platinum or gold as the anode, an electric current may be established by connecting both electrodes to one another and to a milliamperemeter, in which case the patina is not removed. Alternatively, electrolysis may be applied locally, to areas of bronze disease, with an electrolytic pen and without immersing the object.

Electrolytic reduction is used for iron from both land and marine sites. Electrolytic reduction with sacrificial anodes can be carried out in situ for iron objects in suitable conditions.

A form of electrolytic reduction, consolidative reduction, may be used to strengthen heavily corroded silver. Consolidative reduction involves the steps of reducing, dissolving, and then depositing the reduced silver using partly rectified current.

As in the case of silver, electrolytic reduction may be used to remove the corrosion from lead, and consolidative reduction with partly rectified current may be used to strengthen severely deteriorated and weakened lead objects and to restore the surface decoration. Chlorides have been removed from aluminum alloy aircraft through electrolysis.

Electrochemical reduction

Electrochemical reduction makes the object to be cleaned the cathode and puts it in contact with a more noble metal, used as anode, in an electrolyte that establishes a potential difference without an externally generated electric current, thereby reducing the corrosion while oxidizing the anode.

Hydrogen reduction

Hydrogen reduction has been used in Sweden on the Wasa iron artifacts and more recently for large marine iron objects, such as the cannons on the *Mary Rose*. The Swiss National Museum in Zurich has developed low-temperature (50° to 200°C) hydrogen plasma reduction, which is safer for the operator and avoids microstructural changes to the metal.

Monitoring the removal of chlorides

Measuring chlorides that are released during desalination can be carried out with simple titration kits, electronic chloride meters, and chloride-specific ion meters. More sophisticated analytical means include ion chromatography and inductively coupled plasma mass spectrometry (ICP-MS). Determining the amount of chloride remaining in the object can be more challenging and destructive to the object.

Corrosion inhibitors

Blocking chlorides with chemical corrosion inhibitors through either local application or immersion is one means of stabilizing metal. Common corrosion inhibitors for copper and copper alloys are benzotriazole (BTA), 2-amino-5-mercapto-1,3,4-thiadiazole (AMT), and a combination of BTA and AMT. Locally applied corrosion inhibitors for copper alloys include silver oxide, silver nitrate, and zinc powder. For iron and steel, the most common corrosion inhibitors have been tannins. Triethanolamine salt of an acrylamido carboxylic acid (Hostacor IT) and phosphates added to PEG solutions during the treatment of waterlogged wood with iron components have protected the iron from corrosion. Self-assembled monolayers (SAMs) are considered state-of-the-art corrosion inhibitors for some metals such as silver. Carboxylates, especially sodium decanoate, showed good results on heritage objects and have the added advantage of reversibility (Dillmann et al. 2013). BTA and carboxylates show promise as corrosion inhibitors on zinc and brass.

Protective coatings

Coatings are often applied to protect metal objects from moisture and oxygen after cleaning and desalination. Microcrystalline wax, Incralac (a methyl methacrylate copolymer with BTA), Paraloid B-72, B-44, and B-48 N methyl methacrylate copolymers, and ORMOCERs (inorganic-organic copolymers) are among the coating materials used today. Organosilane-based coatings and solgels (3-mercapto-trimethoxysilylpropane; Prop-SH solution) have been used for copper alloys. Conducting polymer films such as poly (3-amino-1,2,4-triazole) have been found to protect silver, copper, and copper alloy artifacts. Sodium carboxylate SAMs have been used successfully to protect iron, copper, zinc, and lead artifacts from corrosion and present the advantage of reversibility (Dillmann et al. 2013).

Preventive conservation

Preventive conservation of metal objects involves controlling the moisture, temperature, and oxygen levels of their environment. Preventive conservation of underwater metals can take place while the object is submerged in situ or immersed in a stabilizing solution in the conservation laboratory.

Preventive conservation instead of, or preceding, interventive conservation

When numerous metal objects are excavated and the availability of conservation hours is limited, objects must often be stored for long periods of time before they can be examined, cleaned, inventoried, and so on. In such cases preventive conservation is particularly important for archaeological bronze and iron, since chlorides from burial render these metals especially sensitive to ambient moisture and oxygen. Small iron and bronze objects from land sites may be stored in desiccated or anoxic conditions, thereby being spared any further deterioration. The Revolutionary Preservation System (RPS) of anoxic and desiccated storage has been used with success for archaeological metals in Turkey (Paterakis and Hickey-Friedman 2011).

Iron that is contaminated with chlorides from land and underwater sites may be stored in solutions of sodium sesquicarbonate and sodium hydroxide or sodium sulfite in order to retard corrosion until desalination can be carried out. The stability of iron may be monitored by measuring the corrosion potential (E_{corr}) of the artifacts in sodium sesquicarbonate and sodium hydroxide solution (Scott and Eggert 2009). The cathodic protection of marine iron involves the use of sacrificial anodes or impressed current. Monitoring the corrosion indicator value by periodically measuring the pH and E_{corr} will determine which objects are most at risk and what is the end point of treatment, that is, when most chlorides have been removed (MacLeod 2014).

Preventive conservation following interventive conservation

For the safe display and storage of archaeological metals after interventive conservation, knowledge of the most suitable materials for storage and display and of the acceptable environmental parameters (levels of temperature, relative humidity, oxygen, volatile organic compounds, and other atmospheric pollutants) is necessary. Environmental remediation as a form of preventive conservation is necessary for the safe display and storage of metal objects both in the short term and in the long term. Preventive conservation after interventive conservation is especially important if chemical stabilization is not entirely successful (see previous section and Paterakis and Hickey-Friedman 2011). Other means of preventing corrosion include sorbents, scavengers, and vapor-phase inhibitors placed in the storage or display case and vapor-barrier films for case surfaces.

SEE ALSO: Archaeological Sciences; Archaeometry; Characterization of Metals and Alloys; Conservation; Deterioration of Metals; Ethics in Conservation; Laser Cleaning; Metallography; Polymers in Conservation; X-Ray Radiography and Material Analysis

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FURTHER READINGS

Conservation of Mosaics

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Definition of mosaics

Mosaics are a type of architectural surface decoration which developed in the Hellenistic and Roman periods and continued through the Byzantine and even early Islamic periods. Mosaics normally decorate floors, but the technique was used for wall surfaces and vaults as well in both private homes and public buildings.

Mosaics are commonly considered to be those pavements that use small cut cubes (*tesserae*) of stone, ceramic, or glass inserted in a bedding layer of lime (calcium hydroxide), supported by a foundation of several layers of lime mortar (*nucleus* and *rudus*) and a stone rubble base or leveling course (*statumen*). The Latin names for these support layers have come down to us through the Roman architect and author Vitruvius. Miniature mosaic panels, using extremely small tesserae (*opus vermiculatum*), were also used as portable decoration or for insertion centrally within larger pavements (*emblemata*).

Other types of ancient pavements can be grouped together under the term “mosaic,” such as pebble pavements, a precursor to cut tesserae pavements, or pavements composed of slabs of decorative stone, often marble, cut into geometric shapes (*opus sectile*), or of a combination of both tesserae and stone slabs (*opus scutulatum*).

Conservation challenges and approaches

The conservation of these pavements, whether in situ as a complete composite, layered structure, linked to the architectural structure it adorns, or within museum collections as a detached surface, presents numerous and varied challenges. The surface of an in-situ mosaic is located at the

interface of a building and the surrounding environment and is therefore particularly exposed to often rapidly changing external conditions and forces. At the same time, an in-situ mosaic is part of a building system, with foundations that link it to the below-ground environment and its changing conditions as well. The dynamic natural environment surrounding an in-situ mosaic above and below ground is the cause of many different mechanisms of deterioration which can negatively impact the condition of a mosaic and its constituent porous materials over time.

The challenge of conserving mosaics whose tesserae surface (*tessellatum*) has already been detached and removed from their architectural context on site is often related to the choice of modern materials used to provide a new support for the *tessellatum*. The environmental conditions within a museum or a storage facility, while generally more controlled than an open-air situation on site, can also contribute to the deterioration of a detached mosaic regardless of the type of support or whether the mosaic has been provided with a new modern support. But the operation of detaching a mosaic from its bedding layers destroys part of the bedding layers and can provoke the loss of or damage to the tesserae themselves to various degrees, depending on the detachment technique used and the skill of the operators.

The conservation of mosaics consists of a variety of activities, some of them preventive measures aimed at controlling the environment of a mosaic in order to diminish the causes of deterioration and thereby slow its rate of deterioration. Such measures include the construction of a shelter, and access barriers and walkways to prevent visitors from walking directly on mosaics, as well as reburial or seasonal protective coverings. Other activities are remedial interventions to restore structural stability to a mosaic by means of adding or applying new materials to replace lost or damaged original constituent materials.

The methods and materials used to conserve mosaics, whether preventive or remedial, have evolved over the centuries, especially in recent decades as a more scientific methodology and

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conservation ethic has been adopted, favoring an in-situ, preventive conservation approach over removing mosaic surfaces to be preserved in a museum or replaced in situ on a new support. The current approach reflects the additional cultural value that a mosaic is considered to possess if it is preserved within its original architectural context and if its original constituent materials are preserved as much as possible, while limiting the addition of new material. In this way, the authenticity of the mosaic is preserved, as opposed to restoring the original decorative image (Roby 2006).

The current approach is also more holistic. Whereas in the past, the more valued figurative component of a pavement might have often been removed from its surrounding geometric decoration, a pavement would now be conserved in its entirety. In addition, the conservation of a collection of mosaics within an entire building or an entire site would be addressed rather than favoring the conservation of its figurative mosaics over nonfigurative ones or of certain types of mosaic pavements over others.

The present conservation methodology for mosaics and other categories of heritage materials includes an initial phase of study and assessment before carrying out a conservation intervention, all of which are thoroughly documented. Interventions are then followed by monitoring of condition and maintenance activities as needed.

A conservation assessment of a mosaic or collection of mosaics should consider three aspects: its significance or cultural importance within a particular region; its condition; and its degree of exposure to environmental and human factors of deterioration. These different aspects can then be assigned a rating for each mosaic, and combined to achieve an overall priority rating for intervention or more detailed study when considering a large collection of mosaics (Roby et al. 2017).

An assessment of condition should normally be carried out by a conservator or conservation technician and can be done at three levels: an initial rapid survey to obtain basic data and set priorities; followed by a detailed condition survey in preparation for planning and executing conservation treatments; and possibly a specialist survey consisting of material analysis of constituent materials and agents of deterioration,

hydrological and/or geological mapping, collection of environmental data, and so on (Stewart 2014).

An important component of assessing condition is determining whether deterioration is active or ongoing, what the rate of deterioration is, and its causes. This will be important in determining priority of conservation action. To do this, it may be necessary to monitor the condition of a mosaic over time, rather than rely on a single inspection.

Deterioration

Mosaics are subject to deterioration from various causes throughout their history, from ancient mechanical damage due to wear and impact, through burial and subsequent growth of tree and plant roots and burrowing animals, to environmental exposure upon excavation (see DETERIORATION OF MOSAICS).

Remedial interventions on in-situ mosaics

The aim of conservation interventions on mosaics is to reestablish their structural stability. This is achieved by trained conservators and technicians using lime-based mortars to carry out a variety of repairs: filling areas of loss of tesserae or original mortar (fills of lacunae and of interstices or joints between tesserae), protecting broken edges of mosaic (edging repairs), re-adhering bedding layers which have become partially separated (injection grouting of voids), and re-adhering loose tesserae to their bedding in their original position (resetting of tesserae).

In the past, and still in some cases, excavated loose tesserae or even modern tesserae have been used to fill areas of lost tesserae, but this is normally not practiced because it compromises the authenticity of the mosaic. Instead, mortar is generally used, while paying attention to its surface color and texture, in order to reduce the visual impact of the mortar within the mosaic. This is done through the careful selection of mortar aggregates such as sand and crushed stone, and sponging of the mortar surface to remove



Figure 1 Lacunae infilling with lime mortar.

Source: Photo: Aurora Ortega de Torre. © 2007 The J. Paul Getty Trust. All rights reserved.

lime and to make the aggregates more visible (Figure 1).

The structural stabilization of mosaics through injection grouting of voids below the surface, generally along the interface between bedding layers, is a relatively recent advance in the treatment of in-situ mosaics (see *GROUTING IN CONSERVATION*). The introduction of this technique has had the most impact on reversing the trend away from the routine detachment of mosaics and relaying them on a new support. In the past, complete detachment was the response to the common deterioration phenomenon of localized loss of adhesion between the bedding layers of a mosaic, as there were no known alternative treatments.

The other significant recent advance in treatment methodology has been the move from the use of cement-based mortars for repairs to the use of lime-based mortars. Such mortars can be made of lime putty or natural hydraulic lime (NHL) or a combination of the two, depending on the type of treatment and the mortar characteristics required. To be effective, the application of lime mortars requires training, and care needs to be taken to avoid the rapid drying out of such

mortars before setting of the lime has occurred. Portland cement-based mortars were commonly used, but are not considered appropriate because of their excessive mechanical strength and salt content which can accelerate the deterioration of the original ancient lime mortars and make its removal in the future very difficult to achieve without damaging the adjacent original materials.

Cleaning is an important component of stabilization interventions because it is necessary to have mosaic surfaces cleaned of dirt and microbiological growth for the mortar repairs to adhere and remain attached to the mosaic. Cleaning is normally carried out using mechanical means such as brushing with soft bristle brushes and some specialized tools such as scalpels and dental pics, together with limited amounts of clean water, often applied by hand pump sprayer and removed by sponge. This can be done effectively without resorting to chemical solutions and biocides. Cleaning is also carried out as part of routine maintenance to remove accumulated wind-blown soil and sand and to remove microorganisms, both of which will promote the growth of plants.

Remedial intervention of mosaics previously detached and relaid in situ

Due to the accelerating deterioration of the thousands of mosaics detached and relaid on site on reinforced concrete during most of the last century, conservation attention has recently focused on saving these mosaics. Such mosaics pose even more of a challenge than conserving in-situ mosaics as the options for their protection are more limited. Reburial and protective shelters are not long-term options if the reinforced concrete has been exposed already for many years. There are two conservation options for such mosaics. The first is to remove the corroded rebar if it is causing damage to the mosaic. This can be done by localized facing of the mosaic surface and temporarily removing the detached part of the *tessellatum*. After removing the corroded rebar underneath, the *tessellatum* is relaid on a new bedding of cementitious mortar.

While this intervention can remove the immediate cause of the deterioration, the long-term solution to conserving mosaics relaid on reinforced concrete panels on site can be to remove the entire support panel and relay the detached mosaic on new bedding layers of lime mortar, similar to the original foundation stratigraphy. This is a difficult and costly operation, however, as removing the concrete can provoke damage to the original tesserae which are weaker than the concrete to which they are strongly adhered. In addition, the original detachment of the mosaics in sections may have led to the loss of rows of tesserae along their edges which could then make their correct relaying in relation to the other panels conjectural. Facing the mosaic and removing it in sections to a laboratory where the concrete support panel is removed, constructing a new foundation of layers of lime-based mortar and relaying the *tessellatum* on them in their original location, are all operations requiring considerable skill and resources, but only in this way can the mosaics be preserved and protected in situ for the long term.

Preventive measures for conserving mosaics in situ

In order to respond to the challenges posed by the exposure and neglect of mosaics on sites, both those on their original foundations and those detached and relaid on reinforced concrete, the lack of financial and trained human resources to address them means that preventive measures, and in particular reburial for those on their original mortar layers, need to be employed (see PREVENTIVE CONSERVATION IN ARCHAEOLOGICAL SITES). Reburial is the most cost-effective means of preventing mosaic deterioration, whether it be for the short or long term (Roby, Alberti, and Ben Abed 2014). However, to be effective it should be designed using appropriate materials of sufficient depth and adequate containment to create a stable environment, and then properly maintained to control growth of vegetation in particular (Stewart 2004) (Figure 2).

Separation membranes are frequently used as part of a reburial design, especially in contact with the mosaic, as a horizon marker and to facilitate reexcavation. However, if the membrane is impermeable it can have negative consequences, as the membrane will promote root growth and other biological activity under it. Geotextiles have been increasingly used in reburials as a separation membrane in recent decades, but they can prevent intimate contact between the mosaic surface and the fill materials and thereby inhibit the free movement of water from the substrate up, which is not characteristic of an effective reburial.

In addition to recreating a more stable environment to slow down deterioration, reburial prevents the mechanical damage resulting from visitors walking directly on a mosaic. If, however, the mosaic is selected to be presented to the public, other means of preventing the public from walking directly on it should be created, either by erecting access barriers beside it or by constructing walkways over it.

The construction of a shelter is a commonly used preventive measure to slow mosaic deterioration on sites by reducing the effects of wetting and drying cycles and temperature fluctuations. Shelters can, however, exacerbate certain



Figure 2 Reburial of mosaic with two fill materials separated by geotextile.

Source: Photo: Christopher Sprinkle. © 2015 The J. Paul Getty Trust. All rights reserved.

environmental conditions which accelerate deterioration if they are not designed to achieve certain performance criteria. Shelters are more costly to design and construct than reburials and they will often require more maintenance, which can make sheltering a less feasible preventive measure in many contexts with limited resources. Therefore, the decision to shelter or to rebury should be considered in the context of long-term site-wide planning based on a site assessment and prioritized action plan.

Such site-wide planning should include a maintenance plan based on periodic inspections to monitor conditions and subsequent maintenance as needed. Maintenance activities for mosaics on site will include cleaning of the *tesselatum* surface, localized stabilization treatments with lime mortar, and vegetation removal. In addition, maintenance and repairs of all preventive measures such as reburials and shelters will need to be part of a maintenance plan that takes into account the site resources and management context.

SEE ALSO: Archaeological Fieldwork; Conservation; Conservation Documentation; Conservation in Museums; Conservation of Polychrome Natural and Architectural Surfaces;

Conservation of Stone and Petroglyphs; Conservation Plans; Deterioration; Ethics in Conservation; Heritage and Sustainability; Heritage and Value-Based Approach; Heritage Management; Value or Significance

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Conservation of Polychrome Natural and Architectural Surfaces

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Overview

The term “polychrome natural and architectural surfaces” encompasses a wide array of materials and techniques used to embellish the natural and built heritage. This array extends to pictographs in natural settings and to polychrome architectural surfaces such as wall paintings, murals, bas-reliefs, stuccowork, and mosaics—in archaeological, historical, and contemporary contexts, on interior or exterior walls, ceilings, vaults, and floors.

Significance and context

Polychrome natural and architectural surfaces are by definition immovable heritage. They are a visual record of beliefs, lifestyles, and technologies, and often signifiers of social status. As integral elements of natural formations or architectural ensembles, polychrome surfaces form the protective skin of the structure and the presentation surface. They can have aesthetic, religious, or cultural value in and of themselves and can represent the defining feature of a site or structure or be part of a larger cultural landscape.

Whether the polychrome surface is in an archaeological, historical, or contemporary context determines to some extent the approach to conservation. Typically, in the case of pictographs (Figure 1) and other rock art, the environment and the landscape (see ENVIRONMENT AND LANDSCAPE) of the work are addressed in order to protect not only the polychrome surface as a work of art but also its context and function as an integral feature of the landscape (see HERITAGE

AND LANDSCAPES). In an archaeological context, the polychrome decoration imparts information about past societies and is part of the archaeological record (see ARCHAEOLOGICAL RECORD). Tool marks and traces of painting technology, as well as any signs of cultural practice, are as important as the legibility of the decoration or the painted scheme (Figure 2). In the case of historical decorated surfaces, if the integrity of the decorative scheme is of importance to the architectural ensemble (Figure 3), then the conservation treatment may include restoration of the decoration where that is missing. For polychrome surfaces such as contemporary murals and polychrome decoration carried out in the context of a living tradition (Figure 4) or when the artist is still living, artists may participate in the conservation process, renewing and in some cases repainting the decoration.

Due to the different contexts and varied types of substrates, plaster, and paint materials, the conservation of these surfaces is complex and must be addressed as an integral part of the larger natural or architectural system to which the surfaces belong. In a broader sense, the preservation of polychrome natural and architectural surfaces is tied to the cultural context in which they were created, and their long-term preservation depends on the local community and other stakeholders—and their awareness of and engagement with their own heritage (see HERITAGE ETHICS).

Deterioration

The deterioration of polychrome surfaces is often linked to larger conservation issues of the formation or structure. This may be particularly problematic in the archaeological context, where natural and architectural surfaces are often exposed to the elements. Causes of deterioration can include environmental influences, natural disasters (e.g., seismic activity, flooding), and human intervention, whether unintended or intentional, and lack of maintenance.

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Figure 1 Rock art site at Cueva La Pintada, Baja California with pictographs superposed on the rock face. Photo: Guillermo Aldana. © 1988 The J. Paul Getty Trust. All rights reserved.



Figure 2 Roman wall painting from the College of the Augustales at the archaeological site of Herculaneum. Photo: Leslie Rainer. © 2011 The J. Paul Getty Trust. All rights reserved.



Figure 3 Historic decorative scheme, Mission San Miguel, California. Photo: Leslie Rainer. © 2005. All rights reserved.



Figure 4 Earthen building at the Royal Palaces of Abomey, Republic of Benin, where polychrome relief decorations are periodically renewed as part of a living tradition. Photo: Leslie Rainer. © 1996 The J. Paul Getty Trust. All rights reserved.

Typical deterioration phenomena include, but are not limited to, structural failure of the substrate, impact and abrasion, exfoliation, spalling, decohesion, and erosion (see *EROSION*) of the substrate; delamination and decohesion of plaster and paint materials; flaking of paint; salt efflorescence; biodeterioration; and alteration of original and intervention materials. Given that the natural or architectural systems of which polychrome surfaces are an integral part are complex, deterioration mechanisms may also be due to a combination of factors, which must be systemically addressed in order to ensure the long-term preservation of the natural or architectural ensemble.

Conservation approach

The conservation approach to polychrome natural and architectural surfaces has developed over time. In the past, decorated surfaces were often detached from their support, removed from their context, and treated as movable objects. However, it is now recognized that a polychrome natural or architectural surface is an integral part of the formation or architecture for which it was conceived (Mora, Mora, and Philippot 1984). With the trend of preservation of cultural heritage in situ since the 1960s, current practice takes a holistic approach to the conservation of polychrome natural or architectural surfaces as parts of a larger system, whether natural or architectural. No painted surface can be conserved without taking into consideration the conservation issues of the site, the structure, or the landscape. The conservation of these surfaces depends on an interdisciplinary team of conservation professionals, composed of conservators of architectural surfaces and/or rock art, architects, engineers, scientists, and documentation specialists, to address the complex and challenging conservation issues with which they are presented.

More broadly, effective management systems are essential to the long-term preservation of polychrome natural and architectural surfaces; and should actively involve key stakeholders—especially traditional owners, caretakers, site managers, building owners, local communities, and governmental bodies—in

order to provide adequate support for heritage, in all aspects of preservation and conservation (Agnew et al. 2015).

A management plan (see *HERITAGE MANAGEMENT*) for the site or building should normally be drafted and implemented prior to addressing conservation issues of the surface itself, except in rare circumstances when the surface is endangered, and must receive urgent treatment, as in the case of natural flooding, or the building of dams in areas with significant polychrome surfaces. A successful management plan will consider public and political awareness of the vulnerability, uniqueness, value, and significance of the polychrome surface and its support and context (Agnew et al. 2015).

A comprehensive conservation plan (see *CONSERVATION PLANS*) for the natural site, structure, or wall and for the polychrome surface and support should consider larger site issues such as drainage or site protection, and structural problems, as well as passive measures and remedial treatments of the polychrome surface and support. This is critical in order to ensure the long-term sustainability of conservation efforts.

Once larger site and structural issues have been addressed, the methodology currently followed in the conservation of these surfaces is based on a series of overlapping and iterative steps, which begin with background research, environmental monitoring, diagnostic investigation, and condition assessment to develop passive measures and remedial treatments. Following implementation of conservation measures, posttreatment monitoring and maintenance should be planned and carried out. All the steps taken in the conservation process, should be fully documented.

Background research

Background research aims to gather information related to the physical history and use of the natural or cultural site, architectural complex, building, or wall. Archival research, the compilation of historical photographs, and oral histories are some of the means by which information about the surfaces and the site may be obtained. Information recorded should include the physical history and use of the site, the technique

of execution, and previous interventions. Comparative studies of similar sites and surfaces, related treatments, interviews with living artists, custodians, or other stakeholders, and examples of ongoing cultural and artistic practice can add to the background research.

Environmental monitoring and climate improvement strategies

Environmental monitoring is used to better understand current conditions and their possible impact on the site, structure, and surface in order to develop appropriate climate improvement strategies. Depending on scope, resources, and needs, this work can be limited to a basic monitoring of the temperature and of the relative humidity or it can be more sophisticated, in which case it might involve the monitoring of more factors: ground moisture, moisture movement inside of walls, surface temperature of walls, air flow, solar radiation, and other site-specific environmental conditions. Data collected from environmental monitoring should be evaluated with respect to the specific deterioration patterns of the polychrome surface, so that environmental causes of deterioration may be determined and appropriate mitigation strategies may be developed accordingly.

Diagnostic investigations

Analytical imaging (see IMAGING) and scientific analysis of original and intervention materials and deterioration products aid in the understanding of the original technique of execution, past treatments, and causes and mechanisms of deterioration of polychrome natural and architectural surfaces.

Analytical imaging includes a range of techniques that is expanding rapidly as technology advances. Currently, techniques such as multispectral imaging (see MULTISPECTRAL AND HYPERSPECTRAL IMAGING OF ARTWORKS), digital image enhancement, reflectance transformation imaging (RTI) (see REFLECTANCE TRANSFORMATION IMAGING (RTI) IN CONSERVATION), photoluminescence of Egyptian blue (see

PHOTOLUMINESCENCE OF EGYPTIAN BLUE) and other pigments, and other imaging techniques can provide information on the composition of paint and plaster materials, the technique of execution, the presence of coatings, and superimposed imagery, which are otherwise difficult to identify. Infrared thermography (see IR THERMOGRAPHY and THERMOGRAPHY), laser speckle interferometry, endoscopy, and radar (see RADAR) are valuable tools for detecting voids behind the surface and anomalies in the stratigraphy of the plaster and substrate.

Today, standard noninvasive analytical techniques include portable X-ray fluorescence, portable Fourier-transform infrared spectroscopy, and fiber optic reflectance spectroscopy (FORS) to identify the materials of the polychromy.

Minimally invasive sampling can provide more precise information than noninvasive techniques. Gas chromatography–mass spectrometry (GC-MS) (see GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS)) and high performance liquid chromatography (HPLC) (see HIGH PERFORMANCE LIQUID CHROMATOGRAPHY (HPLC)) can be used to identify pigment binders (see PIGMENTS AND BINDERS) and organic materials, while ion chromatography may be used for the characterization of salts. Scanning electron microscopy (see SEM-EDS AND MATERIAL ANALYSIS), optical microscopy (see OPTICAL MICROSCOPY), microchemical testing (see MICROCHEMICAL TESTS IN CONSERVATION), polarized light microscopy, and ultraviolet fluorescence microscopy can be used for the characterization of materials and stratigraphy. Other techniques such as X-ray diffraction (XRD), Raman spectroscopy (see RAMAN SPECTROSCOPY IN CONSERVATION), and laser-induced breakdown spectroscopy (LIBS) (see LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS)) can assist in the characterization of constituent materials (see CHARACTERIZATION OF PIGMENTS).

Condition assessment

A condition assessment documents specific conditions of the substrate (natural rock, earth, masonry, wood, plaster), paint, and surface and

should be carried out to better understand current conditions, original technique of execution, previous interventions, and change over time. Conservation documentation (see CONSERVATION DOCUMENTATION) includes recording in graphic, photographic, and written formats and is combined with background research, results of environmental monitoring, and diagnostic investigations aimed at fully understanding materials, conditions, and environmental factors that affect the site, structure, and polychrome surface in order to develop conservation strategies at all levels.

Conservation planning and implementation

On the basis of the condition assessment, which includes environmental monitoring and diagnostic investigations, a conservation plan is developed. This plan must take into consideration sitewide issues, environmental factors, and structural problems as they relate to the polychrome surface. Passive measures and remedial treatments are then developed and implemented. The principles of conservation should be minimal intervention, compatibility of conservation materials with the original materials, stability of conservation materials, and reversibility or retreatability.

Passive measures

Passive and preventive measures may include sheltering, controlling environmental conditions, and, in some cases on archaeological sites, reburial.

Remedial treatments

Remedial treatments may include structural stabilization of the support; plaster stabilization; salt reduction or removal (desalination); reduction or removal of unstable or damaging previous interventions; surface consolidation; readhesion of flaking paint; filling of losses; bioremediation;

surface cleaning; and aesthetic reintegration. Prior to implementing remedial treatments, treatment testing is carried out on mock-ups in the laboratory or in the field. If laboratory-based testing is carried out, further field testing is recommended to verify the feasibility of specific treatments on site.

Structural stabilization

Structural repairs are necessary in the case of roof leaks, capillary rise, structural cracks, poor drainage, and other damage to the site, the structure, or the wall. If structural stabilization will impact the polychrome surface, proper protection should be provided during the structural work.

Plaster stabilization

Voids, cracks, and delaminations of plaster layers have in the past been stabilized with anchors and pins used to physically reattach the plaster to the substrate. Since the 1980s injection grouting (see GROUTING IN CONSERVATION) has typically been used to stabilize plasters, mosaics, and wall paintings in situ. Custom-mixed and commercial grouts have been developed for architectural surfaces. Most are aqueous grouts, but some nonaqueous grouts have also been tested and used in the field. The selection of an injection grout should consider specific properties of the original material and the nature of the void, crack, or delamination to be treated (Biçer-Şimşir and Rainer 2013).

Surface consolidation

Powdering stone, plaster, preparation and/or paint layers should be consolidated in order to reinstate the integrity of the decohesive material. Inorganic mineral consolidants (see MINERAL INORGANIC TREATMENTS) and organic resins have typically been used for surface consolidation. Recently the development of nanomaterials (see NANOTECHNOLOGY AND NANOSCIENCE IN CONSERVATION) for consolidation has broadened the range of suitable materials for surface consolidation. Consideration should be given to the selection of the material, as a film-forming consolidant can create a moisture-impermeable layer

over the polychrome surface, which may lead to unanticipated damage over time, particularly in an uncontrolled environment with fluctuating temperature and relative humidity.

Readhesion of flaking paint

Readhesion of flaking paint requires an appropriate adhesive, which is introduced behind the paint flake. This operation differs from surface consolidation, as it aims to reinstate the adhesion between two intact layers and should not remain on the surface. Conservation adhesives include a wide range of materials, from natural inorganic and organic materials to various synthetic polymers (see *POLYMERS IN CONSERVATION*).

Filling of losses

Typically, losses to earthen-, lime-, or gypsum-based plasters are filled with (repair) mortars similar in composition to the original plaster. In current conservation practice, depending on the site context, losses are often filled to a level slightly below the surface, to distinguish the fill material from the original fabric.

Bioremediation

Bioremediation is necessary when there is active or dormant biogrowth in, on, or around the polychrome surface. Preventive measures can be taken and commercial chemical treatments are currently used; however, essential oils for the treatment of biogrowth are now also being used on stone and are a potential biocide treatment for polychrome surfaces.

Surface cleaning

In many cases, surface cleaning is performed to reinstate the legibility of the decorative scheme and to remove potentially damaging surface accumulations and previous surface treatments (e.g., previously applied and degraded varnishes or surface consolidants). Cleaning techniques can be categorized as dry (e.g., dusting, dry cleaning sponges, and erasers), aqueous (free liquids or gels; see Wolbers 2000), solvent (pure solvents, solvent mixtures, and gels), enzymatic (developed

for the removal of specific materials), and laser (these use a variety of wavelengths; see *LASER CLEANING*).

Aesthetic reintegration

There are many approaches to aesthetic reintegration, depending on the context of the work of art. In current conservation practice, reintegration or inpainting is often minimal, particularly in the case of archaeological surfaces, which have great evidentiary value. With regard to polychromy on natural surfaces such as pictographs, where the superposition of design provides important information on the chronology and cultural significance of the work of art, inpainting is usually not done. On historical painted decoration, it may be important to reinstate the integrity of the architectural scheme, and reconstruction may exceptionally be desirable (Mora, Mora, and Philippot 1984). In the context of living traditions and contemporary murals, when the artist is still living, conservation may take its cue from the artist(s) who created the painted surface, and they may participate in the conservation process, renewing and in some cases repainting the decoration. Inpainting techniques (see *INPAINTING*) have been developed in different schools, regions, and countries. Specific techniques include chromatic reintegration, pointillism, and mimetic inpainting. Stable inpainting materials should be used to avoid changes in appearance or in properties over time. Reversible materials should be used whenever possible to facilitate later retreatment.

Posttreatment monitoring and maintenance

Posttreatment monitoring and maintenance are advisable in order to ensure the long-term preservation of the site, structure, and surface. Monitoring can be carried out using a number of methods including graphic, photographic, and written formats. Maintenance should be performed by trained technicians or by conservation professionals.

Documentation

Conservation documentation (see CONSERVATION DOCUMENTATION) is an integral part of the conservation process. It can be carried out in written, photographic, and graphic form. Laser scanning (see LASER SCANNING) is also used. All stages and aspects of the work should be recorded: conditions, technique of execution, treatment, sample collection, and posttreatment monitoring. Documentation is a valuable tool for the analysis and interpretation of conditions and of change over time and serves as a reference for future conservation needs.

Graphic documentation, too, is often used for recording polychrome surfaces. It can be carried out digitally or by hand, to map conditions directly onto a tablet, on paper or on acetate sheets over drawings, photographic, photogrammetric, or stereophotogrammetric base maps (see PHOTOGRAMMETRY AND STEREOPHOTOGRAMMETRY). Digital recording is done through a variety of techniques, which are currently based on Adobe Photoshop, Auto CAD, or other site-specific or proprietary digital mapping systems. Glossaries of terms have been developed (Weyer et al. 2015; Schmid 2000) for wall paintings.

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Conservation of Stone and Petroglyphs

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A conservation (see CONSERVATION) treatment should have a preliminary phase, in which an object is studied and its condition and deterioration processes are assessed. These are then used to identify the scope of the treatment—at a minimum, halting or minimizing the deterioration and stabilizing the work—and the possible methods to achieve the desired results.

Characterization and identification

Before undertaking a treatment, it is important to characterize the stone, because treatment methods that can be quite safely applied to one type may damage another; for example, acidic solutions used to clean granites will degrade limestones.

Ideally, characterization (see CHARACTERIZATION OF PETROGLYPHS) will go beyond the simple lithotype identification to include factors such as porosity, pore size and distribution, the presence of other minerals, especially those sensitive to water, and the stone's structure and mechanical strength. These characteristics may be more important to the deterioration and treatment of a stone than its mineral composition. For example, different limestones decay in very different ways, and some tuffs become more subject to water damage after some consolidation treatments.

Once a material has been characterized, a literature search should be carried out to see what treatments have been used in the past.

It is also extremely useful to find other examples of the same stone in situ, in order to observe its behavior in other conditions and

after treatments. Clearly tests should always be carried out before starting treatments.

Description and documentation

Documentation (see CONSERVATION DOCUMENTATION) is a key aspect of any treatment, though it is often underresourced in terms of time, funding, and means. While there is no universal glossary for stone conservation, ICOMOS-ISCS (2008) provides a useful starting point for condition reporting, although it is skewed toward outdoor architectural monuments.

Complete documentation should also include original working techniques (tool marks, joins, fills, etc.), details of applied decoration (paint, gilding), previous interventions (patination, fills, etc.) and full details of the present treatment. Each new phenomenon should be described using the tripartite structure of the ICOMOS glossary: it should have a unique descriptive term, a written, unambiguous definition, and a clear illustrative photograph.

In association with this documentation, environmental monitoring should be carried out, preferably in the long term but at least in the medium term, in order to record factors that could affect the stone's condition.

Treatment planning

The data collected should help determine the causes and the nature of the deterioration, and hence make proposals for treatment. Ideally the treatment should form part of a medium-term to long-term conservation site management plan (Loubser 2001). If the site is a museum or a collection, the plan is likely to be much less complicated than if it is an open-air site with many stakeholders (see CULTURAL RESOURCES MANAGEMENT).

One factor that it is important to clarify between stakeholders at this moment is the desired goal of the intervention: the level of

treatment, what future conditions the work will have to support, and what aesthetical treatment is required, if any.

In general, the first option that should always be considered is no intervention at all, except perhaps monitoring. This is especially important in the case of rock art, and particularly on open-air sites. In those contexts, even small interventions can significantly change site dynamics and radically accelerate deterioration. Hence it is especially important to carry out small-scale tests—ideally, tests monitored over a period of time—prior to any treatment.

Another option is not to intervene directly on the stone but rather to protect it from deterioration by employing preventive conservation (see PREVENTIVE CONSERVATION IN ARCHAEOLOGICAL SITES). However, the previous caveat about treatments with potentially damaging consequences still holds true: in many cases, supposedly protective measures have caused an acceleration in degradation.

Generally current practice prefers *minimal interventions*, though it is not always clear exactly what this means, especially if the final goal of the treatment has not been clarified. It is also worth bearing in mind that, if the stone is in a fragile state, a minimal intervention designed to stabilize it means that after the treatment the stone will probably still be quite fragile and will require a follow-up maintenance program that should guarantee its well-being.

Cleaning

Cleaning may be carried out for many reasons, from aesthetical ones (e.g., removal of accretions obscuring the stone) to conservative ones (e.g., removal of corrosive black crusts from limestones). The desired results should be carefully considered, as cleaning always involves some degree of stress or damage to the underlying stone—or perhaps even the removal of transformed original material.

The level of cleaning is often context- and culture-dependent to a high degree. For petroglyphs, it is essential to maintain the natural patina (rock varnish), which both protects the

stone and contains material by which the petroglyphs can be dated. In Italy, for example, it is generally considered correct practice to keep oxalate patinas on archaeological stone and sometimes to retain, as part of the work's history, the artificial patinas applied during restorations.

There are several broad categories of cleaning, and the systems involved vary from cleaning of large-scale archaeological monuments to precision cleaning of minutely carved objects.

Water cleaning

High-pressure water or steam cleaning is generally not considered suitable for archaeological material. For large surfaces, a more controllable method consists in using compressed air to produce fine water sprays or atomized water, in the form of a fine mist. Cleaning occurs through the heightened solubilizing activity of the water, not through water pressure. However, the systems require constant supervision from trained conservators, to avoid excessive cleaning and release large amounts of water.

Further, many stones are unstable in the presence of water, and larger objects may contain water-sensitive components (metals, wood etc.)

Chemical cleaning with solvents/solutions and poultices/gels

When treatment requires the chemical transformation or solubilization of extraneous materials (gypsum crusts, coatings, calcified surface grime, etc.), chemical agents can be applied in cellulose fiber or clay poultices or in gels thickened with polysaccharides, cellulose ethers, silicon esters, and so on. These reduce the evaporation of the chemicals—and hence toxic vapors—and increase possible contact times. Possible complications are related to the regulation of the cleaning levels, residues and reaction products, the safe disposal of waste, and the difficulty of large-scale work. Materials applied range from organic solvents to detergents and acid, alkaline, or chelating solutions.

Laser cleaning

Sometimes lasers give results unobtainable by other means. They are, however, expensive, fragile for site work, and often slower than other methods; and they may cause damage or staining.

Mechanical cleaning

These methods often provide fine control over the removal of adherent extraneous material, though they can cause damage, especially if the stone is more fragile than the material to be removed. Apart from handheld tools (brushes, scalpels, dental tools, hammer, chisels), there are powered tools such as ultrasound ablaters, pneumatic or electric gravers, microhammers, microdrills, and so on. Often these tools are used (together with chemical or water cleaning) to reduce the thickness of deposited material before microabrasion.

Air abrasion and microabrasion

There has been much development in the field since the beginning of the twenty-first century: the tools available range from small portable instruments to large-scale systems that still maintain fine control levels. Jet diameters range from fractions of a millimeter to centimeters, pressures from tenths of an atmosphere upward, and abrasive materials from carborundum down to plastic and cork powders. Abrasive methods work most effectively and safely on uniform deposits; frequently they are used to finish a surface “regularized” by chemical and/or mechanical methods. An experienced operator can achieve very fine gradations of removal, but incautious use can provoke pitting, scratching, and erosion. The dispersal of the abrasive particles can cause problems, particularly in public spaces.

Variations include mixed water/particle systems and, recently, the use of dry ice abrasive; the latter adds a thermal component to cleaning and eliminates the problem of abrasive powder collection.

Biological cleaning

Research on the use of biological agents for cleaning is going on, and at least one product—based on sulfate-reducing bacteria—has been marketed. Biological agents are highly selective and self-limiting, but for the time being the possible problems are slowness, the small-scale character of treatments, and residues; and they require narrow temperature, pH, and humidity ranges to work.

Removal of biological growth

A key but difficult area. The growth of microorganisms and plants—or their removal—can cause severe damage to stone, but chemical treatment can be problematic: biocides and herbicides are frequently toxic for other lifeforms, they often have undesirable physical/chemical characteristics (surfactants), they may cause staining, some materials (alcohols) may act as nutrients. It is unrealistic to expect stone, especially outdoors, to remain sterile, but no treatment plan should rely solely on regular use of biocides. A preventive approach should be considered.

Recent research has included bioinhibiting coatings for open-air archaeological surfaces, while UV light may be a possible solution when treating unpainted surfaces.

Consolidation and consolidants

Introduction

When analyzing stone condition and selecting appropriate treatments, it is important to distinguish between the need for consolidation and the need for adhesion, though there may be overlap. However, a material that is good at consolidation is frequently a poor adhesive, and vice versa.

Consolidation is required when a stone is weakened at the microscopic level or powdering. An ideal consolidant will be physically and chemically compatible, will penetrate a substrate, will remain *inside* while curing, and will leave the stone still porous, so that it can be *treated again* if necessary.

The effectiveness of a consolidant depends greatly on a stone's porosity, strength, and composition. These parameters vary greatly between lithotypes; and consolidants vary considerably in their efficacy, depending on stone type and the condition at treatment (Wheeler 2005).

Effective consolidation also means that the consolidant stays inside the stone as it sets or cures. But when the liquid containing the consolidant evaporates, it tends to draw the consolidant to the stone's surface, where it may form a crust; this means that the method of application frequently makes a big difference to whether a consolidation works or not.

Types of consolidants

Numerous materials have been used for the consolidation of stone, and research is very active.

One of the most commonly used consolidants for stone is ethyl silicate or tetraethyl orthosilicate (TEOS), which is widely available commercially in many different varieties: pure, diluted with various solvents, elasticized with hydrophobic additives. In its natural state it is a low-volatility liquid and has better penetration and retention than many consolidant-solvent combinations. Major disadvantages of TEOS are its cost and its long curing time (20–30 days).

There is debate as to its long-term suitability for nonsilicate stone (e.g., limestones, marble), given its lack of chemical affinity with it and possible decay. However, in the short to medium term, TEOS appears to be at least as effective as other materials.

Other inorganic materials used on some lithotypes include nanodispersions of silica in water and nanodispersions of lime in alcohols, though they can have problems with good penetration. There are also ammonium oxalate, ammonium phosphate, and barium hydroxide.

Many organic materials, especially synthetic resins in solutions or dispersions, have also been used, though often these are better suited as adhesives, owing to their poor penetration and film-forming characteristics. However, good results have been obtained for smaller-particle acrylic microdispersions, though there is discussion about their long-term stability.

Adhesives and joining materials

It is frequently necessary to join separate pieces of stone. These may be separated fragments, distinct parts originally fixed together, or later additions applied for aesthetical, protective, or functional reasons.

An effective adhesive should have good penetration *between* pieces of substrate but poor penetration *inside* the substrate. Traditional adhesives included natural resins, cements, and molten lead, often combined with metal pins or cramps, while in more recent times synthetic resins such as epoxies or polyesters have been used.

These methods have been refined to aid reversibility and reduce damage from metal corrosion—it is now good practice to use soluble resin barrier coatings prior to applying adhesives, to employ corrosion resistant (stainless steel, titanium, carbon fiber, fiberglass) pins, and, where possible, to tailor treatments more strictly to needs: to eliminate pins where possible and to employ more reversible adhesives.

To reduce the invasiveness of these treatments still further, there is experimentation with screw-held, spring-loaded, or sliding pins, rare-earth magnets instead of adhesives, and external or internal frameworks designed to hold the parts together. Due to the greater complexity of these systems, they tend to be employed in museums or indoors (Podany 2009).

When there are cracks or fissures in stone, but not full separation, possible treatments include injecting an adhesive or a grouting mortar. Prior to treatment the crack must be sealed, to prevent outflow of the injected material. However, it is difficult to control the process and to verify the result.

Fills, coatings, and protection

Once a work in stone has been stabilized and cleaned, it is frequently good practice to fill cracks and at least some voids, particularly if the object is exposed to further deterioration processes: losses frequently allow the penetration of water

or extraneous materials, causing further deterioration or allowing plants or microorganisms to colonize.

The filling material should be stable and physically and chemically compatible with the substrate and have an acceptable appearance. Often this involves mixing stone powder and/or pigments with a suitable binder, though the choice of binder will depend on the stone type, the desired appearance, and whether it is used indoors or outdoors. Binders for carbonate stones are usually lime-based, and those for sandstones are silicate-based. Synthetic resins or waxes have been used for highly finished, transparent, or reflective surfaces, though there may be problems of removal, color change, and stability in general.

If the stone is fragile and is subject to wind or water erosion, it is often useful (albeit a short-term expedient) to employ plaster shelter coatings: a thin layer of fine mortar is pressed onto the stone, so that it acts as a sacrificial layer against a source of erosion. This technique is most commonly used for limestones or marbles, as is the more recent (and related) use of oxalate or phosphate solutions to consolidate the stone and form a permeable but resistant calcium oxalate or phosphate coating for surface consolidation or protection. Bacteria have also been used to create a biocalcified protective layer.

Another frequently used protection is water-repellent coatings, especially for outdoor stonework. The most common materials are silicon and fluorinated polymers, although there is some debate as to how long they last, especially on the various stone types. In many cases similar coatings, or even microcrystalline waxes, are applied to indoor stone to protect it against airborne deposit or people who touch the stone.

Unfortunately there is an increasing call for anti-graffiti coatings on cultural property, though these need to be evaluated carefully prior to use: they are often similar to water-repellent coatings but tend to be less permeable and possibly more difficult to remove.

Once again, it is very important to weigh up whether the application of treatment products, even fillings, and especially protective coatings, is desirable and will not lead to destabilization or the disruption of a current equilibrium and to

further problems, especially in the case of Rock art and petroglyphs.

Aesthetical treatment

The question of the final aesthetical treatment can be extremely complicated, since it brings together a wide range of cultural, art-historical, and methodological factors, and aesthetical approaches can range from completely hands-off reconstruction to full-scale reconstruction. This is not the place to consider the multiple ramifications of the issue, so the discussion will be limited to a few more standard methods employed in some of these treatments.

The question of fills was briefly discussed above. For finding a fill material that imitates or resembles a worn stone, usually an inorganic binder is used (lime mortar or silica dispersion, or even TEOS) with powdered stone and/or pigments. In some cases the fills are laid at a slightly lower level than the surrounding stone, deliberately “declaring” the loss, or are left with a surface finish or color that distinguishes them from the original stone. Imitative fills—especially of moderately or highly finished stone, or of semitransparent stone—are difficult to achieve with these binders and, as mentioned above, pigmented synthetic resin or wax binders have often been used.

Sometimes parts are reconstructed. They can be made by using filling materials, synthetic resins casts, or even 3D printers; but sometimes they are made from stone. When stone is used, sometimes the material is chosen to be as similar as possible to the original, but generally some characteristic is used to *indicate* the substitution: the stone may be of a different color or type, or the surface may be finished in some distinctive way. Other materials are generally tinted to match the original, as there is no danger of confusing them with the original stone.

Finally, the stone itself—particularly sculptures or decorative works—may be retouched or treated with an artificial patina for situations where the appearance is uneven, or where fills or stone inserts are visually disturbing. Colors are usually applied using nonpermanent binders, for example watercolors for indoors, or pigments

mixed with reversible synthetic resins such as aldehyde resins, or products used for a surface protection. These tints may be transparent or a whitewash—an opaque layer applied to hide stains.

Future maintenance

Once any conservation treatment is completed, the work should be subject to programmed follow-up inspections that monitor its well-being and ensure the continuing validity of the treatment.

SEE ALSO: Cements, Mortars, Binders; Conservation; Conservation of Polychrome Natural and Architectural Surfaces; Nanotechnology and Nanoscience in Conservation; Polymers in Conservation

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FURTHER READINGS

Conservation of Vitreous Materials

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Vitreous materials include glass, high-fired ceramics such as china and porcelain, and any type of ceramic that has a glaze or glassy surface or matrix, such as faience, stonepaste, and frit. Many of these have similar physical natures and properties that are closely related. Only glazes on low-fired ceramics fall into a somewhat different category, as the glazes are similar to glasses but with varying substrates (earthenware or terracotta). Knowing the chemistry and physical properties of silica-rich materials is critical to selecting the materials needed for conservation treatment. Natural resins have been generally abandoned for treatment use as they are not as stable, dependable, or predictable as modern synthetic resins.

The three major *active* conservation interventions are *consolidation*, *adhesion*, and *loss compensation*. *Passive* conservation management involves climate-controlled storage with year-round monitoring. *Consolidation* may be defined as the strengthening of porous and permeable materials using a dilute resin. It can simply be termed “adhesion in three-dimension.” The primary reasons for consolidation include stabilization, prevention of additional deterioration, or strengthening of an object for handling. *Adhesion* of fragments, or assembly, is one of the most common purposes of conservation treatment, as separate fragments may not be presentable or intelligible. *Loss compensation* is a *restoration* technique that is often carried out in order to provide additional structural support or for aesthetic enhancement for museum display. This is a complicated subject, too detailed to be covered here.

The eventual disposition of an object, or groups of objects, should certainly be considered before

any intervention is carried out, whether the object is to be housed in storage, studied, published, or placed on display.

Consolidation

China, porcelain, and glass

China, porcelain, and glass are virtually nonporous and nonpermeable, have minimal porosity (<1%), and therefore do not require consolidation. However, their deteriorated or weathered surfaces may require consolidation; this is especially true of archaeological vitreous materials that have fragile, friable, or lifting weathering layers. Even in these cases, the glass itself and the high-fired ceramic bodies of china and porcelain remain nonporous, and an application of a consolidant on the undeteriorated areas is not necessary as it would simply coat the surface.

Faience, stonepaste, and frits

Faience, stonepaste, and frits are vitreous materials that have a silica-rich matrix, with a glaze or glassy surface. The surfaces can be compromised much as with the group above, but the body or matrix can also suffer as it is more porous and permeable. The deterioration can manifest itself in many ways, from breakdown of the silica matrix, resulting in breakage, or a weak structural stability. This can be caused by an aggressive burial environment or contamination with soluble salts. Consolidation may be required for both the surface and the underlying silicate matrix or body.

Treatment

The most common consolidants are synthetic resins applied in dilute form. Solvent-based resins are very effective, but in some cases, a water-based acrylic colloidal dispersion may be a suitable choice.

Prior to consolidation, deteriorated surfaces should be examined carefully and properly

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documented (written documentation and/or photography) and permission must be received to carry out the intervention. This may seem irrelevant, but considerable information has been lost by the omission of these steps. Furthermore, if the object is an important artifact from an archaeological or anthropological site, information and samples may be required for dietary analysis, wear, use, dating, or provenance. Consolidation may interfere with these analyses and therefore should not proceed until these questions are resolved, or samples are taken for analysis.

Choice of consolidant

Ideally, a consolidant should be dilute enough to penetrate and strengthen the weakened or loose surface or silicate substrate. For solution resin polymers, this translates into a solids:solvent ratio with a low viscosity. A resin concentration too low will penetrate well, but may impart little or no strength, while one too high may provide more strength, but will not penetrate deeply. Poor penetration can result in a “surface” consolidation, which is no better than a coating. Solvent resins, by their very nature, penetrate better than water-based emulsions or dispersions, but require more care and higher safety measures. Water-based consolidants may be useful especially when very large areas need to be consolidated and the use of solvents is almost impossible.

Although numerous solvent resins are available, and many have been used for consolidation, *Paraloid B-72* stands out as the best choice. It is a stable acrylic copolymer, reversible, and non-yellowing, and has known solubility. It has a very low viscosity in solution, particularly at low concentrations (5–15%). It has a moderately high glass transition temperature (T_g) (40 °C) and can be used safely in nontoxic solvents. It has very good strength and yet is permeable to water, if the consolidation is used as a pretreatment to desalination.

Solvent choice is important, not only for the resin penetrability, but also as a health and safety concern. Early consolidation recommendations often suggested a very slowly evaporating solvent such as toluene or xylene, but these should not be

used for two reasons: These solvents are highly toxic, and solutions have a significantly higher viscosity (Rohm and Haas 1983). Solutions in acetone or in acetone:ethanol are preferable, as they are less toxic and penetrate better. For example, *Paraloid B-72* in acetone (5%) is half as viscous as *Paraloid B-72* in toluene (5%), meaning the consolidant should penetrate twice as deeply. In reality, other factors may influence the penetration of the consolidant, including the application method, ambient temperature, and humidity. The various application methods include brushing, spraying, immersion, and capillary draw (see below).

The consolidant solution should be prepared to achieve the desired result. In some cases, weathered layers are so thin and fragile that touching the surface causes loss, and even a light wind or uncontrolled breath can cause the layers to lift and fly away. A very low concentration (<3% w/v) may impart little or no strength, while a high concentration (>15%) may not penetrate at all. Often a 4–5 percent solution is ideal, but instances of open gaps and lifting surfaces may require a 15–20 percent solution (or a thicker water-based colloidal dispersion such as *Primal WS-24*). This needs to be assessed for each class or group of objects being treated and simple testing with a few different solutions often answers the question. Several different concentrations (5%, 7.5%, 10%, and 15% w/v) should be prepared, and if kept sealed, can be used and reused. *Paraloid B-72* solutions can be quickly made by weighing the resin, placing it in cheesecloth tied with cotton string, and suspending the cheesecloth/*B-72* in a jar of acetone (measured out to the correct amount). No agitation is required; even 150 g will be dissolved in 1 liter of acetone in one to two hours.

For warm or hot climates, a small amount of ethanol can be added (e.g., 90% acetone:10% ethanol). High quantities of ethanol are not recommended because ethanol is extremely hygroscopic and attracts water to itself and can compromise the *Paraloid B-72* solution.

Another acrylic that has proven useful for the consolidation of large loose or friable surfaces is the colloidal dispersion *Primal WS-24*. It is supplied in water and visually appears similar to the acrylic emulsions, but has several different properties (Koob 1981). The very small particle

size and charged particles keep the dispersion from settling out, and the viscosity is much lower than acrylic emulsions (but much higher than solvent resins). One additional benefit is the neutral pH (7.0), whereas acrylic emulsions are higher (pH 8–10). The strength of the acrylic resin is similar to Paraloid B-72 and it has a similar Tg (40 °C). The white dispersion dries clear and is readily soluble in acetone. Primal WS-24 concentrations are made simply by diluting the supplied Primal WS-24 with deionized water. Because it has a higher viscosity, dilutions should be in the range of 10:1 (water:WS-24) to ensure maximum penetration.

Without question, the water-based Primal WS-24 does not penetrate as well as Paraloid B-72 in solution, but its advantages include the lack of solvents (no health hazard), appropriateness for large applications, and lower associated costs.

Applications

The consolidant is generally introduced or applied by brush or pipette. Spraying and immersion are not recommended, as these techniques may cause the weathering or loose surfaces to be dislodged or lost. It is often sufficient to introduce a small amount of consolidant along the edges and allow it to be drawn in by capillary action. In this manner, the consolidant gently finds its own way through the open and permeable layers, strengthening and binding the layers as it dries. Entire consolidation is not recommended as this “seals” and coats the surface of the china, porcelain, or glass and may trap moisture underneath. This can potentially lead to other stabilization problems.

A consolidated surface may be very weak until the consolidant has fully set and all the solvent has evaporated. For both Paraloid B-72 and Primal WS-24, excess consolidant can be cleaned-up easily using acetone and a soft brush, constantly rinsing the brush in fresh acetone. Cotton swabs or toweling are not recommended as they may disturb the surface and leave cotton fibers attached to the B-72.

Work conditions may need to be modified for extreme environmental conditions. Outdoor, on-site archaeological conservation should

be avoided unless the working area is shaded. Indoor and shaded areas will be cooler and more comfortable than working in the sun, and more stable and better controlled for applying consolidants.

Reversing a consolidation treatment is not always practical as the consolidated area might swell and dislodge.

Adhesion

Adhesives are primarily used to assemble broken fragments of vitreous materials. Numerous adhesives have been recommended, but few provide consistent results. Some guidelines for selecting adhesives are: the adhesive should not damage the object, during either application, curing, or aging; it should bond well; it should be removable or “reversible” without damage; be “water” clear; remain stable; and be easy to use with consistent results (Koob 2006).

Two completely different adhesives are recommended for the repair of vitreous materials: Paraloid B-72 and epoxy resin adhesives. Although there are many others, these have become the most popular and familiar. Paraloid B-72 adhesive (discussed above for consolidation) is made up as a thicker resin:solvent solution and sets by loss of solvent. It has a moderate strength, which is especially suited for earthenwares and terracottas, but can also be used on stoneware, porcelain, china, and glass, as well as faience, stonepaste, and frit (Koob 1999). Epoxy resin adhesives are more complex thermosetting resins. They are two-part systems consisting of a “resin” and a “hardener” and when mixed cross-link over time to a solid, insoluble polymer. There are several very good-quality “conservation-grade” epoxy resin adhesives (Table 1) whose working properties, setting times, and stabilities vary (Koob 2006).

Paraloid B-72 and epoxy resins have advantages and disadvantages. They behave very differently and require significant experience to master. The advantages of Paraloid B-72 adhesive include the above-mentioned stability, reversibility, fast setting time, and low cost. In addition, Paraloid B-72 is a thermoplastic resin,

Table 1 Epoxy resin adhesives commonly used in conservation.

<i>Epoxy</i>	<i>Refractive index</i>	<i>Viscosity (cps)</i>	<i>Working time (hours)</i>	<i>Setting time (hours)</i>	<i>Stability (years)</i>
Hxtal NYL-1	1.52	200–300	8–12	48–96	≤100
Epo-Tek 301	1.539	100–200	2–4	4–8	≤50
Epo-Tek 301-2	1.564	300–600	6–8	16–24	≤100
Fynebond	1.551	Moderately low	8–10	24–35	≤50
Araldite 2020	1.553	130	6–10	16	≤50

so joins can be easily moved, after setting, using a hair dryer. The only notable drawback of B-72, specifically on glass, is the fine air bubbles that develop within the join as a result of solvent loss. For this reason, the epoxy resins are preferred for clear glasses.

Epoxy resin adhesive disadvantages include the potential to yellow, particularly when exposed to high light levels (Down 1986), extremely high strength, very long setting times, short shelf-life, and cost. The extremely high strength can compromise the glass, china, or porcelain; if it is bumped or dropped, the adhesive will not fail and the object will break somewhere else. Epoxy resin adhesives are also virtually insoluble when cured and very difficult to remove.

Preparing Paraloid B-72 and epoxy resins for use as an adhesive

It is highly recommended that Paraloid B-72 solutions be made fresh by conservators, especially for ceramics and glass. Koob details the preparation and use of Paraloid B-72 adhesive for both ceramics and glass, including detailed recipes and step-by-step instructions (Koob 2006; 2009).

In general, epoxy resin adhesives do not require any special preparation, but precise weighing and mixing are very important. They are supplied in two parts and one should always read the manufacturer's recommendations for use, the *Materials Safety Data Sheets*, and the specifications for shelf-life and storage. Epoxy resins are slightly toxic during handling, so gloves should be worn when mixing. Cured epoxy resins are not deleterious to health (Skeist 1977, 327).

Application of Paraloid B-72 and epoxy resin adhesives

Careful planning is required before any repair or assembly is undertaken, no matter what the adhesive. All fragments should be clean, dry, and arranged in a logical order for assembly. This is particularly important for epoxy resin adhesive joins, as they cannot be moved once the epoxy has cured. It is generally suggested that a "dry-run" be carried out to see in what order pieces should be joined. This is generally done with clear tape or masking tape.

Techniques of assembly

Paraloid B-72 Once the order of assembly is determined, the tape is carefully removed and the fragments are arranged in the order that they will be joined. Porous substrates or bodies should be primed or sealed before the Paraloid B-72 adhesive is applied, but nonporous china, porcelain, and glass do not require this step. *Priming* creates a nonporous, nonpermeable "seal" that allows the adhesive to make a better bond or join to the surface. It provides a more compatible surface to bond to, allows for more even application and film formation, and slows down the evaporation and setting of the adhesive.

Priming can be done using a dilute solution of Paraloid B-72 in acetone (5–10%). It is similar to consolidation, so if broken fragments have already been consolidated, they do not require being primed. The adhesive is then applied along one edge of the fragment to be joined and a "piece-by-piece" assembly is carried out, checking all joins as the

assembly progresses. Depending on the size and weight of the fragments being assembled, joins may be held, taped, or positioned until the adhesive has set. The time required for the Paraloid B-72 to set varies considerably (minutes, hours) with the size and thickness of the fragments being assembled and ambient temperature. A binocular microscope is a valuable tool in examining the joins to ensure they are correct.

A more advanced technique that works well with very thin china, porcelain, and glass is to completely assemble all the fragments with tape or small clamps across the joins and introduce the Paraloid B-72 along the cracks. This requires thinning the adhesive (25–30%) but can be very effective. It is commonly used for epoxy resin applications (see below).

Epoxy resins Epoxy resin adhesives are generally not recommended for porous and permeable vitreous ceramics such as faience, stonepaste, frits, and soft earthenware and terracotta glazed materials, since the epoxy resin soaks into these porous fabrics and causes irreversible darkening and staining. They are best suited for high-fired ceramics and glass. Epoxy resins are very different than solvent resin adhesives and they can result in beautiful repairs. Epoxies can also be selected to match a specific refractive index of glass, but require absolute care and attention in their preparation and use.

Epoxy resins can be applied using similar methods as Paraloid B-72 (above), either by piece-by-piece direct application or by capillary draw after taping all the pieces together (generally preferred). Epoxy resins have also been successfully used to stabilize cracks in high-fired vitreous materials. For capillary draw or “wicking-in” to cracks the epoxy adhesive should be used within the first hour of mixing, when its viscosity is lowest. Excess epoxy resin should be cleaned-off the surface of a material as soon as possible after application; otherwise, very strong solvents or mechanical removal may be necessary which poses a risk of damaging the surface. Uncured epoxy resin adhesive can be easily cleaned-off using acetone or ethanol.

Work environment for adhesive use

The difficulty of working in hot climates has been mentioned, but it should also be noted that neither Paraloid B-72 nor any epoxy resin adhesives will provide consistent and dependable results if the humidity is unduly high. If the humidity exceeds 60 percent, it is difficult to work with any adhesive.

Passive conservation

Passive conservation management approaches involve climate-controlled storage with year-round monitoring. Proper packing, housing, shelving, and cabinetry are all important in maintaining a safe and stable storage environment. Open storage with air movement is recommended for most vitreous materials, but this is not always practical for fragments. This subject has been researched extensively and is far beyond the scope of this *Encyclopedia* entry.

SEE ALSO: Conservation; Conservation Documentation; Conservation Science; Deterioration of Vitreous Materials; Ethics in Conservation; Glass and Faience; Preventive Conservation in Archaeological Sites

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Conservation of Waterlogged Materials

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Organic materials are among the most perishable materials archaeologically. They have been used for centuries to create tools, weapons, conveyances, utensils, shelter, clothing, leisure activities, storage containers, and even intricately decorated works of art and ritual objects, but their ubiquity is not always reflected in the archaeological record. However, in certain environmental conditions, such as anaerobic ones, these materials can survive remarkably well. Anaerobic (or anoxic) conditions occur most commonly when air is excluded from the burial matrix as a result of water saturation. Without oxygen, microorganisms that might otherwise consume the organics cannot thrive. Anaerobic conditions may occur in marine environments, but they are most common in the sediments at the bottom of lakes and rivers, in wetland areas such as peat bogs and marshes, and in urban environments where centuries of discarded materials contribute to a raised water table. Locally they can also occur inside well shafts and privies on otherwise dry sites.

When excavated, anaerobic sites rarely yield only one or two artifacts but instead give up large quantities of material. Often the volume of the material found poses tremendous logistical challenges. For example, excavations carried out between 2005 and 2013 at the Theodosian Harbor in Istanbul revealed over 35 ships, ranging in date from the seventh to the tenth century AD (Koçabaş, Özsaıt-Koçabaş, and Kiliç 2012). Similarly, the recovery of the *Vasa* in 1961 produced not only the 600 cubic meters of oak that comprised the ship itself, but also over 40,000 artifacts, many of which were also comprised of organic material. In addition to the logistical challenges posed by the size and volume of many of the finds, there are also time constraints that may

impact their treatment. Once organic materials are removed from their burial environment and oxygen is reintroduced, they become susceptible to renewed microbial attack. Additionally, there is the risk of uncontrolled drying, which can result in severe shrinkage, deformation, and cracking. Systems for keeping organics wet (such as water tanks or sprays), supports for heavier materials, a knowledge of the materials involved, and, above all, a preservation plan are all necessary components for the successful retrieval and conservation of waterlogged organic materials.

Wood

The individual ways in which waterlogged organics deteriorate in the burial environment and the sort of intervention that is necessary after excavation are dependent on both the structure and the chemical makeup of the material. For example, waterlogged wood can appear to be very robust and well preserved when it is initially excavated. Tool marks are often visible and may contain sufficient detail to make it possible to identify not only the types of tool used, but even the use of the same tool on multiple pieces of wood within the same or neighboring structures—which facilitates the study of working patterns (Historic England 2010: 21). However, the surface appearance of wood is frequently deceiving. Structurally, wood is composed of a number of cells made up of three major components: cellulose (45–50%), hemicellulose (15–35%), and lignin (20–35%). Prolonged exposure to anaerobic conditions can lead to the hydrolysis of the cellulose and hemicellulose in the cell. As these are lost, what is left behind is a lignin skeleton filled with water. This skeleton has structure, but little strength. The water inside the cells is providing structural support by swelling the cell walls and filling the cavities (lumina) in the cells. If the water is allowed to evaporate, the cells, too weak to withstand capillary forces, will collapse. Cellular collapse is an irreversible process that has macroscopic results such as cracking, warping, splitting, and

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delamination. In order to avoid cellular collapse, a bulking agent must be introduced before drying.

Since as early as the nineteenth century, archaeologists and conservators have experimented with a number of materials as bulking agents. Alum (hydrated potassium aluminum sulfate) was used extensively in Scandinavia from 1850 to the 1950s. The idea was that the alum, a water-soluble material, could penetrate the wood and reinforce the structure through the formation of alum crystals inside the wood. Important Viking-era finds, such as the Oseberg ship in Norway and the Hjortspring boat in Denmark, were treated with this method. Unfortunately, as is now understood, the alum did not penetrate as deeply as was thought. Additionally, physical damage occurred as the alum crystallized; and, because alum is hygroscopic, damage continues to occur when there are fluctuations in humidity within the storage or display environment. Additionally, sulfuric acid was produced during the application, and it continues to damage the wood. As a result, the method has been abandoned, and mitigating its effects remains a focus of international research. Another historic treatment that is rarely used is the acetone–rosin method. This method was more promising, but the health and safety implications of working with large quantities of heated acetone forced most practitioners to abandon it.

Today a number of chemicals are in use for the treatment of waterlogged wood. They can be divided into two categories: reversible and irreversible compounds. Reversibility, although rarely fully achievable, is an important concept for conservators, since it recognizes the fact that, despite our best efforts, objects will require future retreatment; and it aims not only to facilitate that, but also to ensure that any additions made to artifacts can be removed with minimal impact to the original material. Polyethylene glycol (PEG) is perhaps the most widely used compound for treating wood reversibly. It is a water-soluble polymer that can be applied in a number of ways; timbers may be sprayed with it or immersed in it. Different molecular weights of PEG may be used, depending on the species and degradation of the wood; however, research focused on the behavior of PEG during freeze-drying has suggested that low molecular weight PEG may not freeze, and this may cause future problems. Like wood, polyethylene glycol is hygroscopic,

which means that it absorbs and desorbs moisture from the environment. This can mean that, in environments where the relative humidity (Rh) fluctuates, polyethylene glycol may become sticky and may trap dust or promote mold growth. It may also serve as a transport mechanism for impurities and salts in the wood.

In some countries PEG is expensive or difficult to acquire. Sugars (such as sucrose) have been used as alternatives to PEG. Like PEG, they are water-soluble and can theoretically be reversed as needed. Successful results have been reported; however, fermentation of the sugar solution has also been reported (Hoffmann 2009), and there are concerns about whether the sugar in the wood may attract insects when the objects are in storage or on display. Recently, research into sugars has focused on the potential of sugar alcohols such as lactitol (Hoffmann 2013, 93) and of nonreducing sugars such as trehalose (Imazu et al. 2016).

Irreversible treatments, employed for the preservation of waterlogged wood, include the *in situ* polymerization of monomers using gamma radiation, the use of Kauramin, a melamine resin (Hoffmann 2013, 97–104), and the use of silicone oils (Tejedor 2012). These treatments tend to be significantly shorter than PEG or sugar treatments and the results reported are often very good; but it is important to note that, when wood is treated with these materials, the compounds irrevocably cross-link with the wood, complicating future treatments. One of the advantages of these materials is that they appear to make the wood less susceptible to changes in Rh after treatment.

The efficiency of wood treatments may be measured by both quantitative and qualitative criteria. Quantitative criteria include water content, density, weight change, and measurement of dimensional shrinkage. Qualitative measurements include visual criteria such as color, presence or absence of cracks, changes in surface morphology, but may also include treatment time, cost, reliability, and the personnel and skill levels required for a successful treatment. Due to differences in wood type, preservation, and treatment methods, it can be difficult to reliably compare results from one site or object to another. Documentation techniques, such as 3D scanning, laser scanning, X-radiography, photography, and drawing, are important for recording

condition both before and after treatment and for facilitating long-term comparisons. The chemical characterization of the wood's condition, which uses Fourier-transform infrared spectroscopy (FTIR), nuclear magnetic resonance (NMR), and X-ray diffraction (XRD), is increasingly being employed to report the ratios of lignin, cellulose, and hemicellulose in the wood, as well as the presence of iron and sulfur.

Since the late 1990s, research has focused heavily on the role of acid formation in the deterioration of treated wood. When wood is buried in anaerobic environments, it may accumulate sulfur compounds that may be oxidized after treatment; this results in the formation of acids, including sulfuric acid, which can further degrade the wood. The presence of iron compounds in the wood appears to catalyze these oxidative degradation processes. These processes are often initiated by periods of high Rh, which suggests that it is important not only to attempt to remove iron and sulfur compounds during treatment but also to maintain a stable environment after treatment, when wooden artifacts are in storage or on display. Recent work in waterlogged wood conservation has also focused on the development of new, bioinspired consolidates that are based on materials such as cellulose acetate and chitosan. Although some promising experimental results have been reported, significant work is still needed before they can be used to treat actual objects.

Nonwood organics

Leather is a durable and flexible material that is made by tanning animal skin. Vegetable tans were most commonly used in the past, although since the end of the nineteenth century chrome tanning has been the most common form of tanning. In addition to the tanning agent, dyes may be introduced to color the leather, and oils may be applied to make it more water-resistant. Leather survives well in wet anaerobic environments, especially those where the pH is mildly acidic. Some leaching of the tannins may result from prolonged exposure to waterlogged environments. On terrestrial sites, leather may become discolored and blackened from humic

materials in the burial environment and from the reaction of ferrous irons with tannins, and this may result in the hardening of the leather after treatment. Iron concretions and marine encrustations may also obscure the surface of the leather. Delamination or splitting into two discrete layers may also occur. Although this has sometimes been attributed to issues with the original tanning, it may be more reflective of areas of discontinuity in the collagen fibers. If leather is allowed to dry naturally from the wet state, the collagen fibers that compose it cross-link, causing embrittlement and shrinkage. Treatments have therefore focused on introducing lubricants before drying.

Historically, leather treatments were often drawn from the leather industry and materials such as lanolin, oils, and leather dressings were applied to help soften the surface and lubricate the collagen fibers. These treatments often had to be periodically refreshed, and the overoiling of the leather through time may have led to additional damage. Today polyethylene glycol 400 is most frequently used to pretreat leather and is followed by either controlled air-drying or freeze-drying.

Freeze-drying is a technique by which water is removed from an object through sublimation. It requires specialized equipment, but the advantage is that the technique eliminates surface tension and is therefore gentler on the object, posing fewer risks to cellular and/or fiber structures than rapid air-drying. Freeze-drying may be used for a range of waterlogged materials, including wood, although the size of the freeze-dryer may impose limitations on the size and amount of material that can be successfully treated.

Woven materials such as textiles or basketry may be found in archaeological contexts. These are most frequently composed of cellulose-based plant fibers (such as flax, hemp, or cotton) or protein-based animal fibers (such as silk or wool). The diversity of these materials, coupled with the fact that they are not found as frequently or in the same quantities as wood and leather, explains why less has been published on their conservation. Preservation varies according to the method of construction and the environmental conditions. For example, protein-based fibers tend to survive best in acidic conditions, whereas cellulosic materials survive best in alkaline

environments. Furthermore, woven materials may incorporate a variety of other materials, such as dyes, mordants, metals, and surface impregnants, which may all influence the preservation of the material. Pre-deposition use, such as wear, also impacts postexcavation preservation. As the items deteriorate, dissolution becomes a real risk, as does the potential for breakage and tear. Support (on netting or sieves) is frequently necessary in order to handle the material; and, when removing surface dirt, care must be taken to ensure that fibers do not become abraded or folded. The flexibility of textiles may be improved by the use of a humectant such as low molecular weight polyethylene glycol in the wash water, but cordage and basketry require higher degrees of consolidation and bulking.

Although not strictly organic materials in view of their high inorganic mineral composition, skeletal materials such as bone, antler, and ivory do have significant collagen components. The loss of the inorganic component through chemical dissolution in acidic environments is the greatest threat to these materials, but the collagen may also be lost in an alkaline environment. For robust materials, controlled air-drying may be sufficient; however, in cases where the bone is more fragile, it may be necessary to add a consolidant. The treatment of skeletal materials is complicated by the fact that DNA studies, stable isotope studies, and other analytical techniques may be compromised by the addition of any modern chemicals. It is therefore important to clearly understand and communicate with conservators and researchers about any planned analysis before conservation. In the case of wet human bone, additional considerations may regard the local legislation and the rights of descendant populations.

Although wood, leather, bone, and woven materials are the most commonly encountered waterlogged organics, exotic materials such as coconut shells, tortoiseshell, horn, baleen, apples, and hazelnuts have also been encountered. The International Council of Museums, Committee for Conservation (ICOM-CC) Wet Organic Archaeological Materials working group is an international organization dedicated to the protection, recovery, characterization, and treatment of waterlogged organics. It has built a corpus of publications based on materials presented at its

triennial meetings that provide a good entrée into the treatment of waterlogged organics.

Due to the rapid pace of development, the large quantities of waterlogged organics that can be found at a single site, and the costs in terms of equipment, personnel, and treatment materials, it is becoming more accepted that not everything can be treated. Increasingly, reburial, either in situ or at a surrogate site with a similar burial environment, is being explored as a means of preserving waterlogged organics. Large-scale research projects—such as the Reburial and Analyses of Archaeological Remains (RAAR) project in Marstrand Sweden (Bergstrand et al. 2004)—have set out to study the effects of reburial on archaeological collections and on modern sacrificial samples over prolonged periods. Other multidisciplinary projects, for example the Survey Assess Stabilize Monitor and Preserve (SASMAP) project, have taken a holistic approach to the identification, assessment, and management of marine archaeology sites, developing new techniques for characterization as well as a better understanding of the marine burial environment and of how it is affected by climate change (Gregory 2016). Monitoring reburial projects at terrestrial sites such as Starr Carr and the Rose Theater points to the complex relationship not only between the reburied objects and their environment, but also between the site and its surrounding localities. Land-use changes several miles away can significantly impact the environment on the site and may pose risks for the reburied artifacts. These projects have complemented the development of treatment protocols by generating new information about burial environments and new techniques for characterizing organic artifacts.

SEE ALSO: Conservation Documentation; Deterioration; Deterioration of Waterlogged Materials; Deterioration of Wood; Polymers in Conservation

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Conservation Science

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Conservation science preserves, cares for, and extends the understanding of artistic and heritage objects, along with allied areas of study such as conservation (see CONSERVATION) and archaeology (see ARCHAEOLOGY). Conservation scientists analyze objects in order to identify materials and the extent of deterioration (see DETERIORATION), develop new conservation treatment methods (see CONSERVATION), test materials used in treatments, and determine best practices for object exhibition, storage, and transportation. Conservation scientists have expertise in certain areas, depending on the collection or specific mandate of their museum, gallery, or institution. They may examine paintings, works of art on paper, photographs, archaeological materials, and objects made of glass, ceramics, stone, metals, wood, leather, bone, ivory, textiles, and plastics. The field is therefore applied and interdisciplinary, incorporating aspects of chemistry (whether analytical, organic, inorganic, or polymer science), materials science, engineering, and biology. "Heritage science" is a more recent term that covers conservation science, archaeological science, and technical studies (such as technical art history); also, greater emphasis is being placed on the impact that heritage science has on the economy and on society (Heritage and Golfomitsou 2015).

The beginnings of modern conservation science date back to the nineteenth and early twentieth centuries. The work carried out by founding figures like the German scientist Friedrich Rathgen at the Royal Museums of Berlin, the English scientist Harold Plenderleith at the British Museum, and the American scientist Rutherford John Gettens at the Fogg Art Museum at Harvard set the path of scientific inquiry for examining the manufacturing, deterioration, and preservation of artistic works and archaeological materials (Oddy 2011; Bewer 2010).

The field has grown considerably in the last century and a half. Today conservation scientists may be generalists, concerned with a whole area, such as preventive conservation, or specialists, for example in particular analytic techniques. Still other scientists develop conservation treatment methods with conservators. In order to ensure ethical practice, professional codes and guidelines have been drawn up (see ETHICS IN CONSERVATION) which conservation scientists should follow.

Conservation scientists come to the field by various paths, but most of them begin with an undergraduate degree in some science or engineering field, usually followed by a graduate degree. The opportunity to work on a conservation science topic may come during PhD work or during a postdoctoral or other fellowship. Some scientists choose to take a master's degree in conservation, which allows them a great understanding of the treatments a conservator performs. Others may go directly to a conservation science position.

Materials characterization

Conservation scientists participate in technical studies with colleagues from related fields, in order to gather information about the materials and construction of heritage objects such as wall paintings (see CONSERVATION OF POLYCHROME NATURAL AND ARCHITECTURAL SURFACES), metal objects (see CHARACTERIZATION OF METALS AND ALLOYS; CONSERVATION OF METALS; DETERIORATION OF METALS; and METALLOGRAPHY), and ceramics.

In the multivolume *Artists' Pigments: A Handbook of Their History and Characteristics*, conservation scientists have contributed chapters on specific pigments (see CHARACTERIZATION OF PIGMENTS) that are of use to conservators and other professionals. For example, Kate Helwig (2007) focuses on natural and synthetic iron oxide pigments, covering the terminology, the pigment's properties (spectral reflectance, hiding

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power, permanence, and other chemical and physical properties), its composition (including sources and preparation), its identification and characterization through microscopy, chemical tests, and various analytical techniques, and its use in heritage materials and in various time periods.

Results from the work of conservation scientists may also indicate cultural information such as historic trade routes. In one example, the chemical characterization of amber from 11 different deposit sources in Canada was possible with the help of a number of analytical techniques (Poulin and Helwig 2016). When amber beads from three Thule sites were analyzed and the results were compared with those from the deposit sources, possible tradelinks were identified between a deposit source in Cedar Lake, Alberta, and the Arctic. This example demonstrates the overlap between archaeological science (see *ARCHAEOLOGICAL SCIENCES*) and conservation science, as discussed by Artioli (2010).

Evidence of the presence of anachronistic materials, which are not in keeping with the attributed age of the object, may indicate a forgery, as explained in Paul Craddock's comprehensive guide on determining the authenticity of a wide range of antiquities and artistic creations through technical and scientific study (Craddock 2009).

Deterioration of materials

Conservation science research into materials and the way they degrade, for example by oxidation or hydrolysis, is used to direct conservation and preservation strategies (see *DETERIORATION*). This operation may include setting up an appropriate storage environment to slow down deterioration, perhaps by modifying the relative humidity or temperature.

The extensive body of research carried out by David Scott at the Getty Conservation Institute focuses on characterizing the structure, morphology, and corrosion of ancient and historic metallic materials (see *METALLOGRAPHY*). Members of the European Federation of Corrosion (EFC) also study the corrosion and conservation of metallic artifacts designated as heritage. Such efforts make a significant contribution to our

understanding of the forming and deterioration of metal objects and are a driving force for establishing conservation treatment and long-term preservation protocols (Dillmann et al. 2013).

Mitigating deterioration: conservation treatments

Scientists collaborate with conservators in developing new treatment methods and materials with a scientific basis that can be applied directly to objects (see *CONSERVATION*). Research in this area may address procedures such as cleaning or reduction of soiling, soluble and insoluble salts, and corrosion products; consolidation of weakened and degraded materials; reconstruction of broken elements; and restoration of areas of loss. Case studies of such work can be found throughout conservation and related literature.

Materials used in any treatment must be of conservation grade or archival quality. For example, adhesives in conservation treatments have been rigorously tested for yellowing, solubility, strength, and pH (Down 2015). Such tests often use accelerated aging, whereby, in order to estimate how materials will react over time, samples are exposed to intense environments, for example high relative humidity and temperature, to speed up reactions. This is a method used in other fields but is not an absolute measurement; to be valid, the accelerated degradation pathway has to be the same as the actual degradation pathway.

Mitigating deterioration: environmental conditions and preservation materials

A first step in mitigating deterioration is identifying threats to the heritage material; the Canadian Conservation Institute (CCI) describes these threats in its web resource on agents of deterioration (Canadian Conservation Institute 2016).

Conservation scientists, in collaboration with building professionals and conservators, also work to establish environmental protocols designed to protect collections in exhibitions, in storage, and during transportation. Such work includes developing environmental standards

for display case lighting and guidelines for the relative humidity and temperature ranges appropriate in specific circumstances. It also involves recommending materials, for example for the long-term storage of archaeological objects made of ivory and ceramics, after excavation.

Using only materials designated as “conservation grade” or of archival quality is crucial for the long-term preservation of artistic and heritage objects. Materials in contact with these objects also need to be identified in order for us to ascertain whether they are safe; examples are materials in gloves used to handle collections, materials used for packing and mounting collections, and materials used in storage and display cases. Studies have shown, for instance, that wooden storage furniture commonly used earlier on to house archaeological collections gave off gaseous volatile compounds such as acetic and formic acid, which reacted with metal objects to form new corrosion products.

Analytical techniques and scientific methodology

Analytical techniques are depended upon by conservation scientists; the rapid development of emerging technologies associated with them results in an increasingly diverse and sophisticated instrumentation. It is imperative that researchers working with conservation scientists frame specific questions regarding the chemical and physical properties of the objects being studied, so as to determine the line of scientific investigation that employs the appropriate instrumentation and will obtain the most accurate results.

Many analytical techniques applied to art objects are discussed in separate entries in this encyclopedia. Numerous books serve as references designed to guide their use and give an overview of the extensive range of techniques applied to heritage materials (Artioli 2010; Stuart 2007). Commonly used techniques are polarized light microscopy (see OPTICAL MICROSCOPY); fluorescence microscopy; X-ray fluorescence (XRF; see X-RAY FLUORESCENCE SPECTROMETRY (XRF)); scanning electron microscopy with elemental dispersive spectroscopy (SEM-EDS; see ELECTRON MICROSCOPY IN CONSERVATION);

X-ray diffraction (XRD; see XRD AND MATERIALS ANALYSIS); Fourier transform infrared spectroscopy (FTIR) (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)); and gas chromatography–mass spectroscopy (GC-MS) (see GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS)) (see also CHROMATOGRAPHIC TECHNIQUES IN CONSERVATION). The list of techniques grows as testing equipment becomes more portable or improves in capabilities; examples are portable FTIR, portable X-ray fluorescence spectrometry (pXRF) (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)), macro-XRF, and combined techniques like XRF and XRD. The interest in mechanical testing is growing in the field. The conservation scientist needs to focus on the intricacies of the analytical method, any changes or improvements in the technique, the appropriate methods of sampling and preparation, methods for interpreting the data, and their significance in a heritage context. Collaboration is crucial and conservation scientists regularly work with conservators, archaeologists, art historians, and curators to develop new lines of research.

Results must be interpreted taking into account both the instrument used in analysis and the object analyzed. Reference books like *Handheld XRF for Art and Archaeology* (Shugar and Mass 2012) are invaluable, both by giving an understanding of the general results obtained from the instrument and by covering specific groups of objects. Included are chapters on pesticides in ethnographic collections, archaeological sediments, obsidian, Maya ceramics, glass, paintings, and photographs. Organizations such as the Infrared and Raman Users Group (IRUG) and the Users’ Group for Mass Spectrometry and Chromatography (MaSC) ensure that reference spectral data are available for interpretation and provide an opportunity for members to discuss how the techniques can be applied to heritage objects in sample preparation, analysis, data treatment, and interpretation.

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Deterioration

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Definitions

Deterioration can be defined as the process by which something becomes impaired in its form, in its fabric, or in its function over time (Figure 1). It is often used as a synonym of degradation, decay, and damage; however, for some authors, deterioration, degradation, and decay are related to the natural evolution of materials over time, while damage is associated with an instantaneous impact, often of anthropogenic nature. The balance in understanding how change affects both the tangible and intangible aspects that uniquely define each heritage site and object will provide fundamental elements to devise means that will allow the removal or mitigation of deterioration.

Although there are no standardized definitions, deterioration is usually considered to be one of the two possible effects of weathering: deterioration and alteration. Generally, weathering can be described as the natural process that results in the transformation of materials over time, through physical, mechanical, and chemical transformations. It encompasses the changes caused by the passage of time, which are shown as visible aging of the objects or materials. Deterioration is generally considered as a negative condition that is detrimental to the integrity of the archaeological site or object through natural or induced phenomena. It is often associated with material loss, and can include changes in the form, composition, or context of the archaeological heritage. Alteration is associated with the natural evolution of materials, and is not always considered as negative. It may involve the addition of elements, an action that usually happens on their surface. Patina is one aspect of alteration.

Examples of deterioration include structural damage of an archaeological element due to soil

movements, and losses of elements, for example fragments of a mural painting or of building materials. Examples of alteration include changes in color in a material, and biofilm growth on the surface of materials.

Alteration and deterioration may affect heritage in qualitative or quantitative processes of change, at different scales. The analyses provided at each of these levels allow understanding of the different variables of deterioration and alteration, which comprise their condition and type (including defining if they are active or inactive), their location and orientation, their extent and severity, and, if possible, their speed or rate. It will also allow the definition of patterns and trends of alteration and deterioration, and search for potential causes, which will enable devising conservation and management solutions.

Classification

Deterioration and alteration may be classified in various ways, following two essentially different approaches: Some divide them by the effects visible on the archaeological heritage (additions or subtractions), while others focus on the possible causes of alteration and decay (human and natural; physical, chemical, and biological; internal and external factors). It is often easier to see the effects, while we can rarely see their causes, as these may be interconnected and complex. However, it is also easier to explain the causes, which can have a series of different effects, and the published literature therefore tends to use this approach. The most important aspect is to use an organized and hierarchical method in order to systematically analyze the object or site (Magar, Pedeli, and Varoli-Piazza 2005; Pedeli 2014).

Figure 2 attempts to show the most important factors affecting archaeological heritage, using the human and natural division, and separating them according to their potential effects, which may be slow and cumulative, or fast and drastic.

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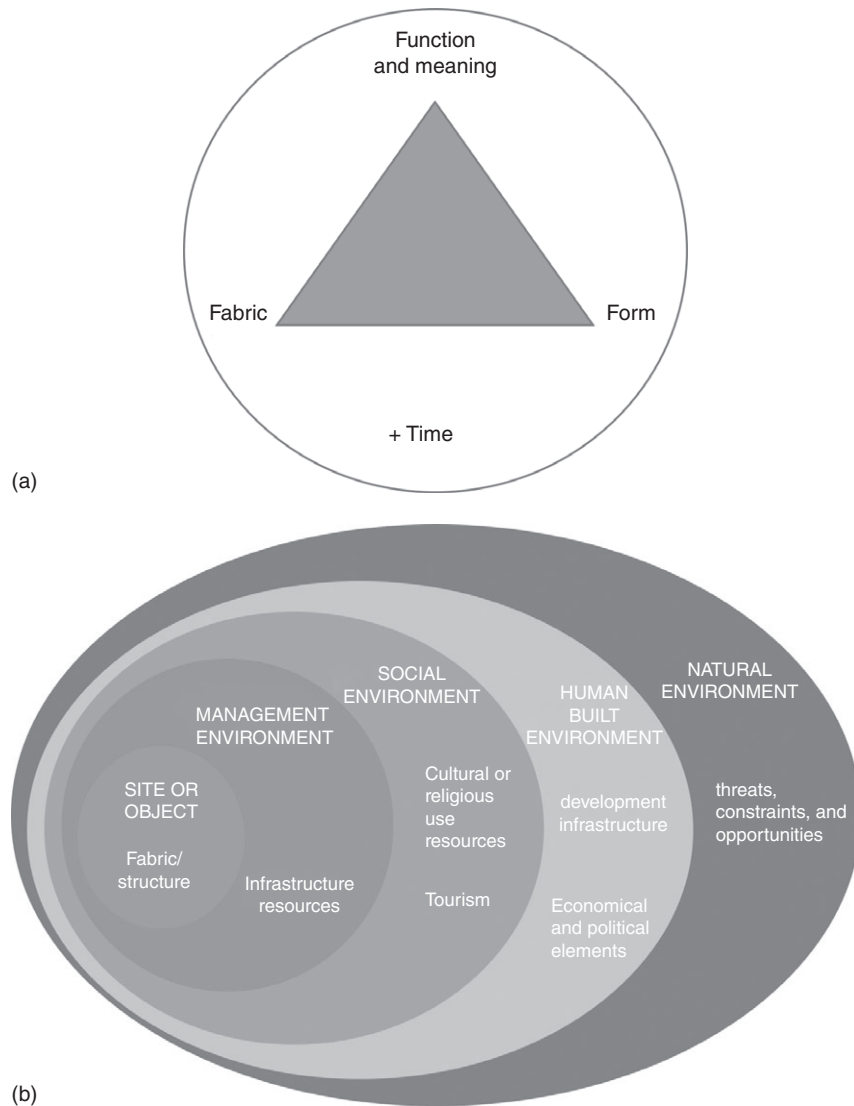


Figure 1 (a) Elements of archaeological heritage potentially affected by alteration and deterioration (modified from Matero 2011, 1), (b) and scales for alteration and decay on archaeological heritage.

The impact of these factors on the physical fabric and form of a site or object, and on their function and meaning, which may be associated with intangible aspects, can be assessed through traditional condition surveys, as well as with cultural heritage impact assessments (ICOMOS 2011). The latter have been developed more recently in order to address greater threats to heritage, including much vaster development projects—for example, mining and extractive

projects, and infrastructure developments—or the impact of climate change—for example, increased coastal erosion, or the thawing of permafrost, which will cause the deterioration of countless archaeological heritage objects/sites that are still buried. Both methods allow understanding of site formation, and the evolution and changes at a site or of an object over time, and define alternatives for mitigation, conservation, and management.

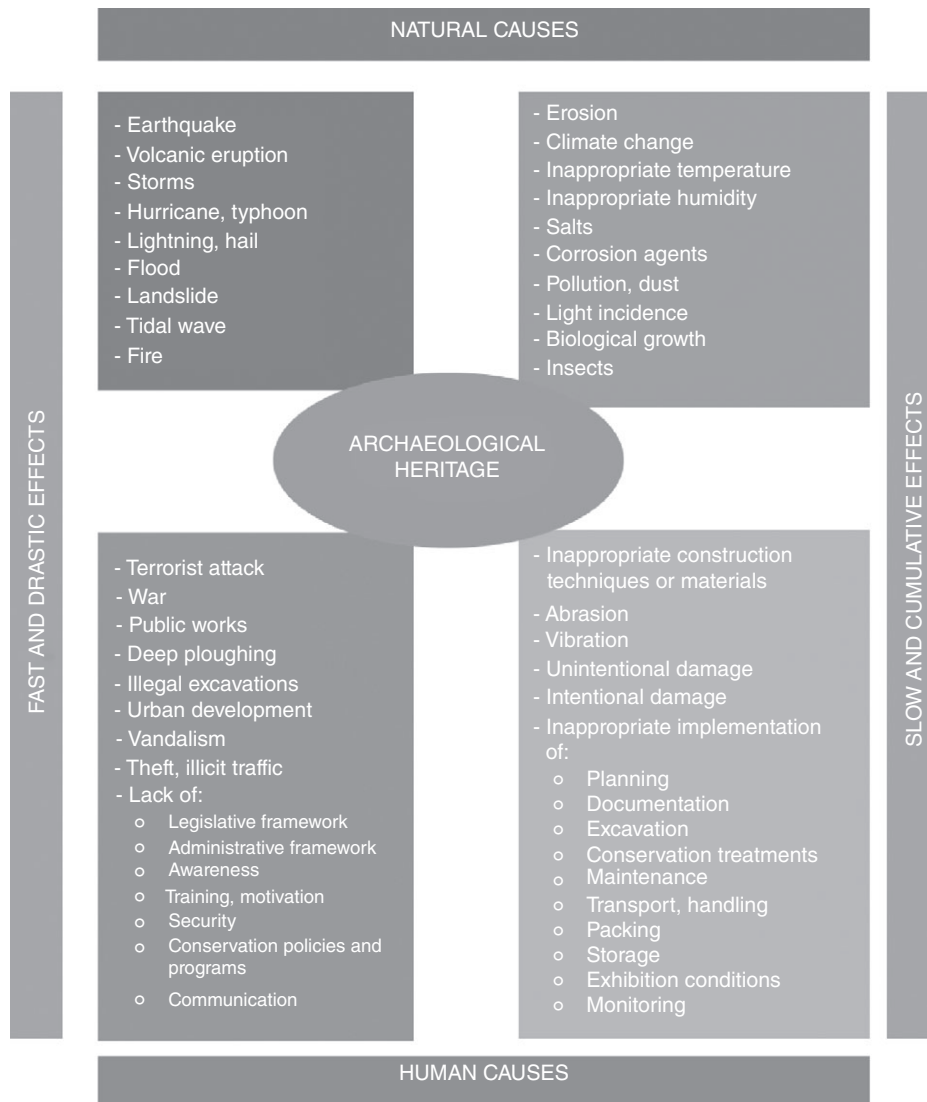


Figure 2 Alteration and decay of archaeological heritage divided according to their causes and the rate of their effects.

Source: Modified from ICCROM (in Berducou 2000, 18).

Perception of alteration and deterioration in archaeological heritage

It is widely accepted that the aim of conservation is to protect heritage from loss and damage. However, how an archaeological site or object is experienced and understood may vary from one context to another, based on cultural beliefs associated with it. In the western tradition, where

a time span separates modern viewers from most archaeological heritage, conservation will consider the often ruined state of those archaeological sites or objects as part of their historical evolution; it will be considered as part of its important significance and meaning. In such instances, only a stabilization treatment will be sought, in order to preserve the character and authenticity of such heritage.

In other cultural contexts, however, especially in sites that still have a symbolic or religious meaning, and where cultural continuity exists, a ruined site may signify a lack of respect; such would be the case in the Buddhist tradition, for example, where a complete restoration and reconstruction may be sought, as an act of religious merit (Wijesuriya 2010). In other places, the role of traditional communities in the understanding of declared archaeological sites has been important to define how change at those sites should be perceived (Ndoro 2005).

Another important element in how alteration and deterioration are comprehended involves a time factor—that is, whether the changes created by weathering proceed from a slow and cumulative effect, or if they are the result of events such as war, vandalism, or acts of terrorism. With the latter, the trauma caused by these violent events usually created an entirely different response from local and international communities, triggering responses for conservation treatments that would not necessarily have been considered appropriate in other contexts, particularly with regard to reconstruction.

In essence, alteration and decay are involved with change over time; and the way society understands those changes, and embraces or rejects their effects, will dictate the measures or acceptance, mitigation or creation of new changes through conservation and restoration measures.

SEE ALSO: Deterioration of Earthen Building Materials; Deterioration of Metals; Deterioration of Mosaics; Deterioration of Stone and Petroglyphs; Deterioration of Vitreous Materials; Deterioration of Waterlogged Materials; Deterioration of Wood

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Deterioration of Earthen Building Materials

XIAO MA

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Earthen buildings require the use of unfired earth. Built as early as 9000 BC (Mileto et al. 2011), earthen buildings appear in both archaeological sites and modern constructions, where their types range from large complexes and historical centers to individual structures and decorated surfaces (Avrami and Guillaud 2008). The types of earthen buildings (adobe, rammed earth, wattle and daub, cob wall, compressed stabilized earth block, etc.) and the construction techniques may vary with people's culture, climate, and resources.

Used as a building material, earth is a mixture of clay, silt, sand, and, occasionally, larger aggregates such as gravel and stones. The geotechnical names of the constituents depend on the diameter of their particles: those with a diameter smaller than 0.002 mm are called clay; those with a diameter between 0.002 and 0.063 mm are called silt; those with a diameter between 0.063 and 2 mm are called sand; and those with a larger diameter are called gravels and stones (Minke 2012).

The forces that keep earthen materials together come from the natural binding forces of clay minerals. Clays are generally made of alumina and silica sheets. Due to their very small size and to their layered arrangement, clay crystals have an extremely large surface area to volume ratio. The binding force originates in the electrostatic charges between the sheet layers of the clay, which are not electrically neutral (they have negative charges). As a consequence, the clay mineral surfaces attract water molecules through the electrostatic forces; and the water molecules penetrate between the layers, causing an increase in the distance and a weakening of the connection between them. This gives the plasticity, cohesion, and volume-change properties of the clay minerals and shapes them into building materials.

When damp, the clay minerals swell and become plastic and cohesive: they deform when an external force is applied, and retain the deformed shape when the force is removed. When dried, they become hard and brittle (Henry et al. 2015).

The earth used in construction normally contains 20–30 percent clay and silt, the remaining amount being sand. This ratio could be found in natural sediments and, if it is not available on the earth near the building site, sand would be mixed with the earth in order to produce a correct mix (Torraca 2009). It is common practice to add earth modifiers or additives during preparation. The modifiers or additives may be inorganic, natural, or synthetic organic materials—for example, fibrous materials (plant and animal fibers), which increase strength and reduce shrinkage cracks; gypsum, lime, cement, asphalts, and bitumen, which are used as soil stabilizers; natural resins, used as adhesives that bond the soil particles together; plant oils and animal fats, which add water repellency to soil and increase hydrophobicity, and so on (Oliver 2008b).

According to the specifics of each construction type, different techniques would be employed to build the earthen structures. For instance, the adobe technique is applied by mixing the earth with water into a liquid state, giving it the desired shape in a mold, then drying the adobe blocks; the rammed earth technique is applied by slightly dampening the earth until it reaches the desired state, then placing it into a mold of the size of the final object, and finally applying a high-energy impact (Velde 2008).

Although earth is one of the most widely used construction materials in the world, it's one of the most vulnerable, too, and earthen materials are susceptible to deterioration. General pathologies of the earthen materials take the form of nonstructural and structural damages. Some common nonstructural damages are delamination/detachment, disaggregation (i.e., loss of binder), flaking (in which thin, small surface layers loosen and flake off), blistering (which looks like bubbles beneath the surface), biological growth (which could be of anything from molds

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to vines and plants), and nonstructural cracking (i.e., cracks that have no effect on the structural integrity of the building; see Cancino and Crosby 2011).

Structural damages include structural cracking (i.e., cracks that affect the integrity of the building and have various shapes—vertical, horizontal, diagonal, X-shaped, etc.), settlement of walls (i.e., the sinking of walls/foundations), lack of physical connections or junctions between the building's components (e.g., between walls), and partial or total collapse.

The factors that can cause the deterioration of earthen building materials may be categorized into three types: environmental factors, human and animal activity, and external factors. These are elaborated upon in what follows.

Environmental factors include wind, excessive moisture, temperature and temperature change with moisture, and vegetation or biological growth.

Wind could cause abrasion and displacement of surface materials in a direct way. It could also accelerate evaporation and deposit deleterious materials on the surface; and, in polluted areas, the sulfur oxide and carbon oxide in the wind could produce carbonic and sulfuric acid with water and thus cause, indirectly, further deterioration of the earthen building materials.

Excessive moisture is a very common factor that causes the deterioration of earthen materials. It can take the form of vapor (through relative humidity or hygroscopicity) or liquid (through condensation into ice, as rain, or as dispersed water and groundwater). The erosive action of rainwater and dispersed water in particular can cause earthen materials to lose their cohesive strength. The subsequent drying of the earthen building roofs, walls, and wall surfaces can further cause the formation of furrows, cracks, deep fissures, and pitting. If left unattended, rainwater can eventually destroy the walls and the roofs, leading to continued deterioration and ultimate collapse. On the other hand, groundwater—possibly coming from a high water table, improper drainage, or seasonal water fluctuations—will rise through capillarity into the wall and the bonding force between the clay particles in the earthen materials will break down, causing the earthen materials to erode, bulge, and cove. The dissolved minerals or salts brought up

by the water can be deposited on or near the surface of the wall as the moisture evaporates, leading to salt efflorescence and deterioration of the earthen fabric. As the earthen materials dry out, shrinkage cracks usually appear and loose sections may crumble (de Teel Patterson and Look 1978).

Temperature and temperature change with moisture could bring on freeze and freeze–thaw cycles. When the temperature drops below 0 °C, ice formation (freezing) would occur (Torraca 2009). When the temperature changes with the moisture in certain conditions, a freeze–thaw cycle may occur, following several steps: (a) saturation of the earthen materials through moisture from precipitations (rain or snow); (b) freezing of the accumulated humidity, causing crystallization and expansion of the water; and (c) thawing of the ice, leading to the presence of water as liquid. This may cause serious damage to frost-susceptible materials (Rainer 2008).

Vegetation or biological growth is a natural phenomenon that can cause the deterioration of earthen materials. The germination of seeds in earthen walls or roofs, where they have been deposited by the wind or by animals, is not unusual; seeds germinate there just as they would in any soil. As a consequence, the action of the growing roots would break down the earthen components or would cause moisture retention, which in turn causes damage to the structure (de Teel Patterson and Look 1978). On the other hand, the lichens may produce acids that could also be deleterious.

Human and animal activity includes human mechanical damage and visitation-induced abrasive wear and tear, inadequate or noncompatible interventions, lack of maintenance or abandonment, and insects-induced or animal mechanical damage.

During the lifetime of earthen buildings, repairing is common and the usage of incompatible materials for repair or treatment could lead to the buildings' deterioration. For instance, the use of high proportions of Portland cement to repair earthen buildings can cause the structure to crack and crumble owing to differences in thermal expansion between the cement and the earth materials, as well as to salt crystallization or to the dissolution cycles of the salts in the cement (Rainer 2008). The replacement of wooden lintels

or doors with steel ones could cause the earthen wall to twist, since the steel lintels are more rigid than the earth ones (de Teel Patterson and Look 1978).

Another common cause of the deterioration of earthen buildings is their lack of maintenance, or even their abandonment. For instance, after an excavation, the earthen buildings in archaeological contexts are subject to extreme changes of environment, which disturb the equilibrium that the structures have reached over a long period of burial. Thus they become more vulnerable to environmental factors of decay, and rapid deterioration could ensue if no right measures are taken for maintenance to be performed (Rainer 2008).

Animals, birds, and insects often live in earthen buildings, burrowing and nesting in walls or foundations, and this undermines, even destroys the structural integrity of earthen buildings. Termites attack the wood members of such buildings (e.g., floors, windows, and roofs, as well as any other cellulose material mixed with the building material), causing physical damage, and sometimes even the destruction of an entire building (de Teel Patterson and Look 1978).

External factors that lead to the deterioration of earthen buildings include earthquakes and other natural disasters (e.g., floods). As adobe buildings have thick and massive walls of low strength, it is possible for the stress caused by an earthquake to exceed the tensile capacity of the adobe material, leading to the formation of cracks, and even to collapse (Leroy Tolles et al. 1996).

It should be noted that it is usually the combination of many factors that prompts the deterioration of earthen materials. Depending on a condition assessment that established the level of deterioration of earthen structures, conservation intervention could be necessary. For instance, for archaeological sites, some common conservation practices include taking preventive measures during excavation, building wall caps and temporary or permanent shelters, reconstructing, backfilling, burial and site stabilization, removal of architectural elements and relocation, and monitoring and evaluation. For built earthen structures, some conservation common practices include cleaning and desalination, grouting,

application of consolidants and adhesives, performing surface treatments, as well as, monitoring and evaluation (Oliver 2008a, 2008b).

SEE ALSO: Adobe; Conservation of Earthen Building Materials

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Deterioration of Metals

STAVROULA GOLFOMITSOU

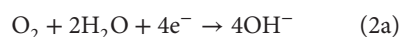
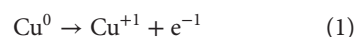
University of Gothenburg, Sweden

Corrosion is defined as the chemical alteration of metals due to interactions with the environment, and is considered a natural process. Except for noble metals such as gold and platinum, all metals will corrode under certain conditions—most typically via electrochemical oxidation processes that produce oxides or other more stable metal compounds (Jones 1996). Corrosion results in irreversible changes to the chemical, physical, and mechanical properties of a metal. The effects of these chemical changes can take a wide variety of forms, from the partial obscuring of the metal surface with corrosion products, to the complete alteration of entire objects (see corroded iron object in Figure 1). While these processes are typically thought of as damaging, the term corrosion is used to describe all reactions of a metal with its environment, many of which might not have adverse effects. Some oxidation processes, for example, lead to the formation of a protective surface oxide which can be desirable and acts protectively. Yet, metal corrosion—the extent and form of which is dependent on several interrelated parameters—in many instances can and does cause severe damage and can lead to loss of an object.

Humans first exploited native metals such as gold, silver, and copper. As knowledge and technologies developed, the number of metals discovered and utilized increased, as well as the ability to combine metals to create alloys. Alloying can improve working and performance properties such as fluidity for casting, or hardness. Today, the metal alloys produced by industry are complex and engineered to meet a wide range of specifications, among which corrosion resistance is a key priority. However, in addition to chemical composition, the way a metal object is manufactured also affects physicochemical properties and hence its corrosion behavior: for example, cast

iron objects are less susceptible to corrosion than wrought iron.

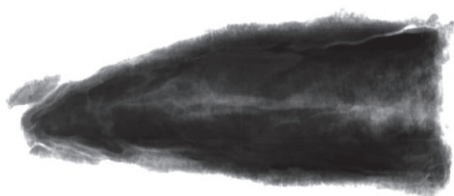
The main factors affecting corrosion are: composition and microstructure of the metal/alloy; the environment (including type, chemical composition, temperature); and the nature of the interface between the metal and the environment where the reactions are taking place (Shreir, Jarman, and Burstein 1994, 1–7). The number of diverse influencing factors and electrochemical processes involved render corrosion science a particularly complex area of study. Nevertheless, a simplified general model for corrosion can be described as follows: most corrosion processes take place through electrochemical reactions between the metal and its environment in the presence of an aqueous or solid electrolyte. During electrochemical processes, anodic and cathodic half-reactions take place. The metal, which plays the role of the anode, loses electrons and becomes oxidized (i.e., its valence changes from zero to a positive value (see reaction 1). The electrons released during the anodic reaction are consumed by a cathodic reaction such as oxygen reduction (2a) or hydrogen evolution (2b). Byproducts of these reactions form metal compounds known as corrosion products.



A number of tools exist that aim to predict whether corrosion could take place and, if so, how quickly this might happen. These draw on two sets of information: (1) thermodynamic methods—used to determine the tendency of a metal or alloy to corrode; and (2) kinetic methods such as the corrosion potential—used to determine the rate at which this will take place. These two aspects are key in determining the likely incidence of corrosion. While an object can be exposed to conditions which could lead to corrosion, the rate at which these reactions proceed may be so slow as to result in negligible



(a)



(b)

Figure 1 (a) Unidentified corroded iron object found during excavations at the Apedemak temple at the Royal City of Meroe in Sudan. The metal has been completely mineralized. (b) X-ray imaging of the object showing the extent of corrosion, with a limited metal core evident from the light area (scanning parameters 120 kV, 4.1 mA, 180 ms). Photos by author.

alteration of the metal. Corrosion theory, though well-developed, is still unable to make accurate predictions regarding the corrosion rate and expected “lifetime” of metal objects due to the multitudinous factors affecting them.

Governing factors

Oxygen and humidity are predominant factors affecting corrosion, but other chemical elements might also trigger corrosion reactions. These elements vary for different metals. For example, the chlorides, found in seawater, coastal air, and polluted groundwater, accelerate the corrosion rate of metals such as copper, iron, zinc, and aluminum. Silver is affected by sulfur compounds, while lead is strongly affected by organic

acids. Similar metal objects exposed to different environments will corrode in different ways.

The type of environment to which a metal object is exposed also has a significant impact on corrosion. In a pure, pollution-free environment, the corrosion rate of a metal will be low in comparison to that of a polluted environment. The main factors affecting corrosion in rural environments are the quantity and frequency of rainwater arriving at the metal surface, humidity and temperature fluctuations, winds, and the presence of corrosion active agents such as chlorides or sulfates. Dust particulates are also important. When deposited on the metal surface, they form a hygroscopic layer that attracts water molecules from the atmosphere. By contrast, urban atmospheres contain pollutants from car exhausts and industrial outputs that result in high levels of nitrogen oxides (NO_x), ozone (O_3), sulfur dioxide (SO_2), and ammonium sulfate ($(\text{NH}_4)_2\text{SO}_4$) (Leygraf and Graedel 2000). These react with moisture and other elements to form compounds such as acids that accelerate corrosion processes.

Oxygen concentration, water content, pH, salinity, and redox potential are but a few of the factors that will determine the corrosivity of soil in burial environments. Some of these parameters vary widely within a short range. The closer a metal object is to the surface, the higher the oxygen content, for example. Aerated acidic soils with high moisture and salt contents are generally corrosive. The resistivity of the soil can be used as a measure of its corrosivity, with low resistivity being indicative of high corrosivity of the soil (Jack and Wilmott 2011). In an underwater environment, where there are plenty of corrosion accelerants such as water, chlorides, and sulfates, corrosion will be fast. Here the most significant factors are salinity, concentration of dissolved oxygen, pollutants, biological factors, and the presence of minor elements, which change depending on depth, ocean currents, and temperature. In addition, gases such as carbon monoxide (CO) and carbon dioxide (CO_2) will also affect corrosion. Water hardness is determined by the presence of calcium (Ca) and magnesium (Mg) ions, which can form carbonates. The formation of a layer of calcium carbonate (CaCO_3) across the surface of an object can act as a protective barrier, limiting the amount of oxygen accessing the metal and

thereby slowing down the overall reactions. In static conditions, metals reach a phase of equilibrium with their environment, causing corrosion reactions to slow down. However, any rapid change in environmental conditions can result in accelerated corrosion. A typical example of this is the effect of excavation, during which the equilibrium between the metal and its environment is disturbed. This, coupled with exposure to increased levels of oxygen, fluctuating levels of humidity and temperature, and other pollutants, will trigger further corrosion processes.

Corrosion forms

The outcomes of corrosion vary. A common misconception is that if a metal shows no visible sign of corrosion, surface oxidation has not occurred. Many metals oxidize rapidly when exposed to oxygen in the atmosphere. In the case of copper and copper alloys, the most common corrosion formed is copper oxide (cuprite; Cu_2O), whereas, in the case of iron and steel the corrosion products are oxide-hydroxides (FeOOH). Air-formed oxide layers are not visible until they are thick enough to cause surface alterations, noted by darkening or dulling of the surface. Oxide layers can also act protectively, slowing down corrosion (passivation). When corrosion is ongoing, it is called active.

As corrosion develops, the oxide layers can be transformed into other compounds, altering not only the composition of the surface, but also the physical properties of the metal/metal alloy. Corroded copper and iron alloy objects are more voluminous than the originals due to the compounds formed.

Preservation of the shape and original surface of a metal object depends on the type of corrosion. Corrosion can be uniform, covering the surface with the same compounds. This type of corrosion is the least deleterious as it tends to preserve the characteristics of an object's surface, and is typical of those exposed in the atmosphere. Localized corrosion can be detrimental to the metal/metal alloy. Galvanic corrosion, for instance, takes place when two metals are in contact, and the more active metal becomes the anode and corrodes, while the noble metal acts as the cathode and is left intact (Cicek and Al-Numan 2011).

Similarly, selective corrosion occurs when one metal in an alloy is preferentially corroded, either because it is more active (e.g., dezincification) or because it reacts with elements in its immediate environment (e.g., decuprification). In alloys, intergranular corrosion occurs around the grain boundaries within an alloy, while transgranular corrosion transverses the grains. Filiform corrosion can take place when a metal is covered with a coating, and crevice corrosion can result when only part of the metal is covered with another material. The most severe form is pitting corrosion, which involves the development of pits which vary from shallow and wide to deep and narrow. The severity of deterioration is due to the creation of a micro-environment within the pit, with autocatalytic reactions taking place which are hard to stop. Differential aeration, meaning variable oxygen exposure to different parts of the metal's surface, results in the development of an electrochemical cell and formation of anodes and cathodes.

Outlook

Corrosion might compromise metallic heritage, but the original surface of objects is often preserved within corrosion layers. A lot of information about the life history of an object can be extracted from a study of its corrosion products. Since corrosion types and corrosion products are a direct result of the reactions between the metal and the surrounding environment, they are often indicative of the conditions to which a metal has been exposed. An example is the presence of corrosion products such as sampleite ($\text{NaCaCu}_5(\text{PO}_4)_4\text{Cl}\cdot 5\text{H}_2\text{O}$)—the outcome of reactions between copper and decomposing bodies in burials (Scott 2016). This part of corrosion science is yet to be utilized in archaeological research. The extended number of alloys in combination with all the above-mentioned parameters make investigation of archaeological objects a complex but fascinating field.

SEE ALSO: Characterization of Metals and Alloys; Conservation of Metals; Metallography; Metallography and Crystallographic Texture Analysis

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Deterioration of Mosaics

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In the conservation literature deterioration of mosaics refers to a wide variety of weathering mechanisms and conditions that occur on the mosaic surface or the underlying foundation layers, resulting in the weakening of its physical state. While in the past only the decorated surface was valued, today mosaics are perceived and treated as a composite architectural surface, which is an integral part of the monument (see CONSERVATION OF MOSAICS). When seen in their original context, mosaics are composite structures comprising of a series of foundation layers, which support the tessellated surface. The materials used in the construction of mosaics vary according to the geographic location, historical period, function in the building (i.e., floor or wall), and level of craftsmanship. Lime mortars with various types of aggregate are used for the foundation layers with a great diversity in composition and thickness. The tesserae are usually made of sedimentary stones, mainly limestone, while ceramic, glass, faience, or shells are used occasionally. Deterioration of mosaics refers to all the weathering forms and processes that affect the mosaic as a whole or any of the aforementioned constituent materials.

The first attempt to define and categorize the causes and types of deterioration of ancient and historic mosaics was made at the first meeting of specialists in 1977 at ICRROM, which gave birth to the International Committee for the Conservation of Mosaics (ICCM, www.iccm-mosaics.org) and produced the first publication on the deterioration and conservation of mosaics (Selvig 1978). Mosaic deterioration was examined in two broad categories: the in situ mosaics and the mosaics in a museum context. Amongst the main causes of destruction and loss of in situ mosaics acknowledged in this first meeting, were agricultural

activity and construction works, followed by mishandling and lack of management. Deterioration processes were attributed to mechanical, thermal, biological, and chemical stresses acting alone or more often in combination. Careless excavation, administrative delays, and lack of experienced personnel were related to the severe damage and extensive loss of detached mosaics. Moreover, the detrimental effects of inappropriate materials and techniques during the detachment of mosaics and their transfer to inadequate new supports were discussed (Bassier 1978; Veloccia 1978).

In the following years ICCM organized a series of triennial conferences, the proceedings of which have recently become available online (<http://iccm-mosaics.org/product-category/iccm-proceedings/>) and constitute the main source of information on issues concerning the deterioration, conservation, and management of in situ mosaics.

A recent literature review on the deterioration and conservation of mosaics in situ (Piqué et al. 2008) reports four broad categories of deterioration factors that affect mosaics throughout their long history of life: (a) intrinsic qualities, (b) historic events, (c) environmental impact, and (d) human actions. The types of deterioration that occur in mosaics can rarely be attributed to a single event or a specific deterioration agent. A combination of events and the synergistic interaction of various agents are usually responsible for the current condition of mosaics. However, the classification of deterioration agents and weathering forms facilitates the examination, documentation, and better understanding of the deterioration mechanisms.

The intrinsic qualities of the original structure refer to its susceptibility to deterioration, which is related to inherent instability of the foundation or poor physical and mechanical properties of the materials employed in the construction of mosaics. Inherent problems include: weakening and failure of mortars due to poor material selection and incorrect mix proportions, erosion of stone tesserae related to their mineralogical characteristics (see DETERIORATION OF STONE

AND PETROGLYPHS), alteration of glass tesserae related to their composition (see DETERIORATION OF VITREOUS MATERIALS), biological colonization on porous tesserae, and differential subsidence and fracturing caused by underlying architectural features that create voids or inconsistencies in the substrate.

In the category of historic events are included natural disasters, reuse or abandonment of the building, burial, and excavation. The effect of historic events in the deterioration of mosaics can be rarely traced with accuracy. Ancient conservation interventions, such as the reintegration of lacunas with mortar, tesserae, or slabs, are often found in ancient mosaics, indicating that deterioration processes were underway during the initial use of the building. In the Near East several mosaic floors depicting human and animal representations were defaced during the Byzantine iconoclasm, in the eighth and ninth centuries, however, the losses were reintegrated with tesserae or mortar which stabilized the mosaic surface and prevented further loss.

Natural disasters, mostly earthquake, fire, and flood, force intense mechanical as well as thermal stresses, which result in severe deterioration and large-scale losses. The impact of major earthquakes, which have occurred in recent times, has been documented in great detail in mosaics that were already exposed at the time of the tectonic activity. Loss of tesserae, fracturing, detachment of the preparatory layers of mortar, and finally collapse of mosaic sections are some of the most significant effects of earthquakes in wall mosaics. Moreover, as a result of the loss of structural integrity, water percolates through the roof and the walls of the building initiating leaching of lime mortars, transfer and crystallization of soluble salts, or freeze-thaw cycles. Mosaic floor pavements are usually less affected by seismic activity, showing mostly structural subsidence and fracturing caused by the collapse of heavy architectural elements over them.

Abandonment and the subsequent degradation and collapse of the architecture also results in severe mechanical damage of mosaic pavements or the complete destruction of wall mosaics. The collapse debris and the gradual deposition of soil over the centuries cover

the mosaics, which remain under burial until they come to light by archeological excavation, construction works, or agricultural activities. Under burial, mosaics suffer damage due to the mechanical loads of the debris, geophysical disruptions of soil, agricultural activity, site erosion, freeze-thaw cycles, organic acids, and other soluble substances present in the soil, root penetration, microorganisms and activity of burrowing invertebrates and mammals (Stewart 2004). However, they gradually reach equilibrium with the burial environment and may remain in a stable condition for a long period of time. Archeological excavation or accidental discovery of mosaics can be beneficial or detrimental to the mosaics depending on the provisions made for their care and conservation during and after excavation. The systematic detachment of mosaics during the postwar period followed by their abandonment in depots or their mounting in reinforced concrete slabs was responsible for the severe deterioration or the complete destruction of numerous excavated mosaics (Bassier 1978; De Guichen and Nardi 2008).

Upon excavation mosaics are rapidly exposed to a completely different set of environmental parameters and a series of deterioration processes are activated. Temperature fluctuations are associated with the differential expansion and contraction of the layered mosaic structure resulting in fracturing and loss of cohesion or detachment between layers. In the presence of water, thermal fluctuations can also activate freeze-thaw and salt crystallization cycles. The effects of these mechanisms on different types of stone and mortars can vary significantly depending on their physical and mechanical characteristics. Soluble salts migrate through the porous mortar layers towards the tessellated surface, which acts as the interface between the mosaic and the atmosphere. Salt efflorescence occurs in the interstices between the tesserae causing disaggregation of the bedding mortar and gradual loosening and loss of tesserae, while sub-efflorescence results in fracturing, exfoliation, flaking, or scaling of the stone (see DETERIORATION OF STONE AND PETROGLYPHS).

The accumulation of soil in the interstices between tesserae, or other irregularities of the surface, retains moisture and provides a fertile

ground for the growth of microorganisms. The type and the rate of biological growth depend on the microclimate and the nature of the stone, which often provide a source of nutrients for microorganisms. Lichens, algae, fungi, and cyanobacteria are the most common organisms found on mosaics. They obscure the mosaic surface and can alter the physical and chemical characteristics of the mortar and tesserae, resulting in increased susceptibility to other types of deterioration.

The rooting of higher plants on or around the mosaic surface is another major threat to in-situ mosaics. Penetration of roots into the tessellatum through existing fractures causes detachment and loss of tesserae, while the expansion of roots into the foundation weakens the entire mosaic structure and results in loss of cohesion and detachment between the underlying mortar layers, often observed on the surface as bulging.

The last category of deterioration agents refers to the human action that is thought to have the greatest impact in the current condition of mosaics. Neglect, mismanagement, lack of systematic maintenance and preventive measures, use of inappropriate conservation materials and methods, and lack of trained personnel are the main problems related to human action. Uncontrolled and increased visitation is known to have caused significant damage to mosaics. Abrasion of soft and already deteriorated tesserae, dislocation and loss is often observed but rarely accounted. The lack of regular inspection and maintenance of mosaics has been a major topic of discussion amongst conservation professional and site managers over the last two decades, yet only a few sites have developed plans for the long-term maintenance of mosaics after the completion of conservation. Last, but not least, recent political conflicts in the southeastern Mediterranean have triggered vandalism, illicit excavation, and trade of mosaics. Although the problem has been acknowledged, the extent of destruction remains unknown.

The variety and complexity of deterioration processes and alterations or conditions that occur in mosaics have lead to major confusion and difficulties in the communication between scientists, conservators, and practitioners. As a response to this problem a glossary has been developed which provides a valuable tool that enables conservators

to use a common language in the description of mosaics and the documentation of deterioration patterns (Alberti et al. 2013), while an updated literature review on the causes of deterioration is soon expected (Roby and Demas 2012).

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Deterioration of Stone and Petroglyphs

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Anyone who has looked closely at a stone monument should be able to identify with the deterioration (see DETERIORATION) of stone and petroglyphs. While there are indeed a number of stone monuments that seem to be little affected by centuries of exposure to the environment, the majority of them are subjected to gradual deterioration, despite how well they are looked after. Thus, the deterioration of stone and petroglyphs constitutes a major international problem of considerable practical interest, with cultural and economic dimensions, which has been attracting the attention of researchers for quite some time (e.g., Schaffer 1932; Honeyborne 2006; Thompson and Dorn 2017).

There are several causes for the deterioration of stone and petroglyphs, each one bearing a recognizably different effect. Some of these causes, such as earthquakes, floods, and vandalism, are sudden and rapid in their effect. Others are slow and more insidious. Such causes include chemical attack, atmospheric pollution, biodeterioration, and salt crystallization. This entry focuses on the most common causes. The aim is to provide a comprehensive and balanced account of these causes which will allow for a better understanding of the problem per se in order to address it more effectively (see CONSERVATION OF STONE AND PETROGLYPHS).

The most common cause of stone and petroglyph deterioration is probably the crystallization of salts. There are many ways in which stone and petroglyphs can become contaminated with salts. In fact, water moving inside stone may contain various soluble salts originating from the atmosphere or the soil or contained within the material itself and/or neighboring materials (e.g., mortar in contact with stone). Other important sources of salts include biological activity or even

some cleaning and conservation (see CONSERVATION) treatments. Unlike water, salts do not evaporate upon drying. Instead, they crystallize either on the surface (efflorescence) or within the pores (cryptoflorescence or subflorescence) of the material. While the former mode of crystallization is generally unsightly but harmless for stone (though it may affect petroglyphs), cryptoflorescence can generate stresses that are sufficiently large to cause localized fragmentation of the material (e.g., Scherer 2004). The precise location at which salts crystallize depends on the rate of drying, the material itself, and the nature of the salts. Nevertheless, it is not unusual for both forms of florescence to occur together (Honeyborne 2006). It is worth noting that the pore structure of a stone plays an important role in determining its resistance to salt crystallization. Fine-pored stones are generally more susceptible than coarse-pored ones, although the latter may also experience high crystallization stresses, once the coarse pores are nearly filled with salt (Scherer 2000).

In coastal and arid climates, honeycomb or alveolar weathering may develop on granular rocks, due to salt crystallization (Figure 1a). Initially, this kind of stone and petroglyph deterioration may form pits and recesses; however, as it develops, the pits may broaden and deepen to form a network of adjacent and/or connected cells across the stone surface. This causes the deterioration of engraved or inscribed surfaces through lateral and/or internal recession (Paradise 2014).

Atmospheric pollution also contributes to the deterioration of stone and petroglyphs (Figure 1b). The main atmospheric pollutants are acidic, sulfur-based gases (e.g., SO_2) and carbon dioxide (CO_2). These are capable of dissolving in rainwater to form acid rain. The latter reacts chemically with calcareous materials (e.g., limestones and marbles), leading to their slow erosion. While stones consisting wholly or even partly of calcium carbonate are the ones mostly affected by atmospheric pollution, non-calcareous stones (e.g., sandstones) may also be affected due to the absorption of products



Figure 1 (a) Honeycomb or alveolar weathering of stone due to salt crystallization (Kronborg Castle, Helsingør, Denmark, 2008). (b) Deterioration due to atmospheric pollution (Charles Bridge, Prague, Czech Republic, 2012). (c) Deterioration of a stone façade along its soft beds (Nicosia within the walls, Cyprus, 2006).

Source: © I. Ioannou.

resulting from the decomposition of neighboring calcareous materials. Calcareous sandstones (i.e., sandstones in which quartz grains are cemented together by calcite) are particularly attacked by sulfur-based acids in the atmosphere. In fact, these sandstones weather more severely than limestones in regions of high air pollution, since the dissolving of a small amount of calcite will release many quartz grains (Honeyborne 2006). Thus, in the presence of heavy acid rain, the surface of a calcareous sandstone may powder away. Even in the absence of heavy rain, however, the acids may attack some of the calcite in a calcareous sandstone, converting it to the more soluble gypsum. The latter is drawn towards the surface in solution and is redeposited upon evaporation of the moisture and drying of the stone. This leads to the formation of a weak skin layer close to the surface of the stone, which peels off when the temperature fluctuates.

Temperature fluctuations are responsible for the development of thermal stresses on the surfaces of stone and petroglyphs. In regions where these stresses can be extreme (e.g., deserts where there is a noticeable diurnal temperature difference), the heated surfaces may expand at rates much faster than the cooler substrate interior. This spontaneous and/or long-term differential expansion (and contraction upon cooling) can initiate surface spalling or exfoliation, thus contributing to the deterioration of stone and petroglyphs.

Deterioration due to frost action may occur by moisture freezing inside the pore structure of a stone. Frost damage mostly appears in the form of cracking; usually it involves the separation of a wafer or lens-like piece of stone (i.e., flaking) from the outer most exposed surface of the material (Honeyborne 2006). This kind of damage may lead to disfigurement of a petroglyph, but it will

not generally affect the functionality of a stone, even though tourists visiting the site may exacerbate the process by touching or pulling the flake from the substrate. On other occasions, however, the stone may be rendered useless by the direct action of frost. This normally occurs when cracks radiate in many directions, thus reducing the material to smaller fragments. The latter form of damage mostly affects coping and cornice blocks and balusters, which are exposed to cold winds and clear night skies. As with salt crystallization, the pore structure of a stone has a similar effect on its resistance to frost action.

The growth of living organisms on stone can be both a blessing and a blight (Doehne and Price 2010). While the presence of lichens and creepers, such as ivy, may contribute an air of age and romance to stone monuments, and provide thermal stability, thus reducing thermal stresses, on other occasions, biological organisms may enhance deterioration caused by physical processes by inducing physico-chemical changes. For instance, filamentous organisms may extend existing structural and other flaws, while biological assemblages may expand and contract upon wetting/drying, thus exerting damaging stresses on the microstructure of stone and on the petroglyphs beneath. Furthermore, the secretion of enzymes and acids by biological microorganisms may contribute to the biochemical deterioration of stone and petroglyphs. It is therefore necessary to find the right balance between appearance and durability in the case of biological growth. In fact, the topic of biodeterioration has gained increasing attention since the turn of this century. Many researchers nowadays focus on the effect of biofilms on the thermal, hygric, and mechanical properties of stone and the possibility of enhancing deterioration by increasing the duration of surface wetting and providing a source of organic acids and complexing agents (Doehne and Price 2010). At the same time, other researchers (e.g., Hess et al. 2008) work on certain biological processes that may potentially offer protection to stone and petroglyphs in the long term: for example, bacterial biomineralization of calcium carbonate and development of oxalate minerals. This strongly suggests that the effect of living organisms on stone and petroglyphs is still very much open to discussion among the scientific community, with

proven negative and positive aspects entering the equation.

Besides the above well-recognized causes of deterioration of stone and petroglyphs, problems associated with material-inherent defects are also common. Such defects (e.g., soft beds, “vents,” and “shakes”) usually become apparent only after the material has been exposed to aggressive environmental conditions (Figure 1c). Sedimentary rocks, in particular, may contain beds of different structure or composition possibly due to geological changes taking place during their formation (Schaffer 1932). These differences may result in weaker areas that weather faster; in practice, this will show up as uneven weathering. While in ashlar stone, deterioration associated with soft beds is of little importance, except in terms of aesthetic appearance, in projecting or free-standing features it may lead to the loss of large masses of material, thus rendering the structure dangerous. The presence of minute fissures (i.e., “vents” and “shakes”) may also have a detrimental effect on stonework in general and petroglyphs in particular. “Vents” are fissures which comprise a source of weakness; these may not be readily visible in freshly quarried stone blocks. However, they become apparent after a period of exposure to aggressive environmental conditions. “Shakes,” on the other hand, are calcite veins which have no harmful effect on stone. They are often observed on limestone and they frequently stand out in relief from the weathered surface of the stone (Schaffer 1932). It is worth pointing out that the effects of salt crystallization and frost damage are different on stones that have marked weaknesses along their natural bedding planes.

Despite the fact that the deterioration of stone and petroglyphs has been well studied over the years, and irrespective of the wealth of available information, no claim can actually be made that finality has been reached, at least on most aspects of the problem. Existing work shows that much remains to be done in studying the properties of various available stones, and in correlating these properties with the observed behavior of the materials in practice. One of the difficulties until fairly recently has been the fact that related work in the past was mostly undertaken by individual investigators. This highlights the need for interdisciplinary thinking during the study of the deterioration of stone and petroglyphs.

Such an approach has in fact been emphasized in recent years, following the recognition of the inherent complexity of the problem, which often combines physical, biological, and chemical processes under the control of geological and environmental factors (Viles et al. 1997). It is therefore anticipated that in the near future, knowledge regarding the deterioration of stone and petroglyphs will be further enriched, to take into account the combined effect of rising atmospheric pollution levels, changing climatic conditions, and inherent material properties. This will undoubtedly allow the development of more effective conservation treatments and practices for the better care and protection of stone and petroglyphs.

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Deterioration of Vitreous Materials

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Glass and other vitreous materials are found at archaeological excavations in a variety of conditions. The condition can range from pristine, where no deterioration is visible, to so heavily degraded that practically all the glass has been transformed into corrosion products. Glass can also deteriorate in the atmosphere. In both cases, the chemical and physical properties of the environment, especially moisture, and the composition of the glass itself are the main factors that determine the rate of deterioration.

Deterioration during burial

Deterioration of the glass surface during burial is generally known as *weathering* and the deteriorated area as a *weathering layer* or *weathering crust*. Water is the primary cause of deterioration of glass; therefore, glass found in dry soils is generally better preserved than glass found in moist soils. The exposure of glass to moisture causes alkali ions (sodium oxide and potassium oxide) in the glass to be slowly leached out and replaced by hydrogen ions. This leached layer is referred to by several different terms: alkali-deficient layer, silica-rich layer, or hydrogen glass. In general, as the proportion of alkali to silica increases, more alkali is leached; potassium is leached at a greater degree than sodium.

Frequently, the weathering crust is found to have a laminar structure, with individual parallel layers ranging in thickness from less than 1 μm to about 25 μm . The deterioration process occurs in a cyclic manner, creating distinct layers within the weathering crust. As additional layers

form, the crust gets thicker and thicker. The final weathering crust can vary in thickness from microscopically thin to so thick that it can easily be seen without a microscope. Although the chemical processes of glass deterioration have been extensively studied, they are not yet entirely understood and cannot be predicted.

In some cases, the alkali-deficient layers protect the remaining glass from further deterioration; they limit access of water to the remaining glass and thus slow down the formation of new layers. Whether the crust is protective or not depends primarily on the composition of the glass and the pH and temperature of the leaching solution. Glass is fairly resistant to acids, and even highly acidic environments will do little damage to the glass unless fluoride or phosphate ions are present. Alkali environments are much more damaging because the molecular framework of the glass, the silica network, is attacked and broken down, eventually causing the total dissolution of the glass. Higher temperatures speed up the deterioration process. Localized differences in the burial environment can result in variation of the extent and appearance of weathering of glass found on the same site, even within a single piece of glass.

Importance of preserving the weathered surface

Unlike corrosion on metals, glass corrodes from the surface inward, making the weathered surface an integral part of the object because it retains the shape of the original surface even if the composition has changed. Details such as incised decoration, the thickness of the glass, and marks relating to the production or usage of the object can only be preserved if the weathering crust remains intact. These types of details contain information that is quite valuable for the technical, art historical, and historical interpretations of the object.

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Preservation of surface details is not the only reason to ensure that the weathering remains whole. The removal of weathering often reveals a very irregular and often pitted surface because air bubbles and debris trapped in the glass during production are exposed as a result of the degradation. The exposure of such a surface can result in misinterpretation of the original appearance of the object and is aesthetically unappealing.

Finally, there is the aesthetic appeal of the weathering itself, especially iridescence, which has become so associated with archaeological glass and is much valued for its beauty.

Visual appearance of deterioration

The appearance of weathered glass can vary extensively. The visual effects of degradation most commonly found on excavated glass are dulling, iridescence, opaque weathering, pitting, cracking of the surface, discoloration, and a total loss of glassy nature.

Dulling refers to a loss of original clarity and transparency that is quite distinct from haziness caused by scratches or stains. It is closely related to *iridescence*, which is a rainbow-like effect on the surface of the glass similar to a thin layer of oil on the surface of water. Both dulling and iridescence are caused by changes in the composition of the surface of the glass altering the refractive index. The many thin alternating layers of air and weathered glass that make up weathering crusts cause interference between reflected rays of light, leading to iridescence.

Opaque weathering also has a laminar structure, but has a much larger number of layers. These layers may be densely held together and penetrate the entire surface or they may be laminating and superficial and easily disturbed. This type of weathering is characterized by opaque areas, usually white, on the surface, gradually penetrating deeper into the glass; this is generally referred to as *opaque* or *opalescent* weathering. At more advanced stages, the color can be black or brown or even a mottled polychrome. The incipient stage is sometimes referred to as milky weathering because of small spots or streaks of white. At the most extreme stage it is termed

enamel-like weathering and is present as a thick covering varying in color.

Pitting can occur when the deterioration starts at a specific point either on or just below the surface, sometimes creating concentric circles around the starting point. When the weathering is lost, a hole or pit is left in the surface of the otherwise undamaged glass. Pitting often occurs simultaneously at individual sites throughout the surface of a fragment. Weathering from individual starting points can later grow into one another.

Cracking of the surface and within the weathering crust itself can be caused by shrinkage of the alkali-deficient layer due to temperature and humidity changes. Often the cracking does not become visible until some time after the glass has been excavated. This is especially true for glasses buried in wet soils.

Discoloration of the glass can be found in combination with any of the above-mentioned types of weathering and is caused by the migration or alteration of coloring ions and other trace elements. The ions can be leached out of the glass or be taken up by glass from the environment. Iron and manganese cause the weathering crusts to blacken, and contact with copper corrosion products can cause green staining. Yellow-brown iron rust stains are also very common. Certain ions, most notably manganese and copper, may change color through oxidation.

A *total loss of glassy nature* occurs when glass is so badly deteriorated that it exists only as a mass of silica gel and has a sugary appearance which is sometimes difficult to identify as glass.

Combinations of several of these manifestations of glass deterioration are usually found on a single object. The extent of the degradation can also differ from one area on an object to another. The thickness of the weathering crust can vary greatly, depending on the chemical stability of the glass and the aggressiveness of the burial conditions. In extreme cases, corrosion products may have completely replaced the original glass. Underneath the weathering crust the so-called *glass core* retains the original composition and color of the glass.

Atmospheric deterioration of glass

Atmospheric deterioration of glass is a type of glass deterioration that looks very different than the degradation that occurs during burial. In fact, it rarely occurs on archaeological glass. However, the main factors that determine the rate and severity of deterioration are the same, namely the composition of the glass and the environment surrounding it, especially moisture. Water from the air is attracted to and absorbed by the surface of the glass leaching out alkali ions. Alkalis accumulate on the surface, creating a localized high pH environment that dissolves the silica network of the glass, which in turn frees up more alkalis that continue the deterioration process.

Koob (2006, 118–125) uses five stages to describe the progress of the deterioration, some of which may occur simultaneously:

1. During the *initial stage* the presence of alkalis on the surface give the glass a hazy or cloudy appearance. When the humidity is lower (below 40%), the alkalis will form fine crystals. When the humidity is higher (above 55%), tiny droplets will form and may even run down the glass, a symptom known as “weeping” or “sweating.” At moderately low humidity (30–50%), alkali crystals and droplets may be present at the same time. A glass in the initial stage can be washed to remove surface alkalis which will remove the cloudy or hazy appearance and slow down the deterioration process.
2. The second stage, known as *incipient crizzling*, involves the same symptoms as the first stage, but at this point the haziness can no longer be washed away. The glass may look perfect when wet, but as it dries the haziness returns. In addition, close examination under low, raking light will reveal tiny silvery lines in certain areas of the glass. These are very fine cracks caused by the cumulative loss of alkali and the breakdown of the silica network.
3. *Full-blown crizzling* is when the cracking of the surface of the glass has progressed further and can easily be seen without a microscope. The cracking goes deeper into

the glass in stage 3 than in stage 2. If the crizzling has not affected the entire surface, it may be accompanied by symptoms of stage 1 or 2. The deterioration of an object may be irregular because of localized microclimates, such as in the interior of a bottle.

4. In the *advanced crizzling* stage, there is distinctive cracking of the glass, which is so deep that the surface is lost. Often flakes of the glass surface can be found around the base of the object.
5. The *fragmentation stage* is reached when the cracking has become so deep that the object loses its structural integrity and falls apart. This may happen with or without any inside intervention such as regular handling.

It is nearly impossible to predict how fast an unstable glass will deteriorate. Some very unstable compositions may fall apart within years of manufacture, or the deterioration may continue for centuries. Progression from one stage to the next may also occur rapidly or over a prolonged period.

Atmospheric deterioration is found mostly on glass with a less than stable composition, although under certain conditions almost any glass will deteriorate. Glasses most likely to have unstable compositions generally date to time periods when glassworkers were experimenting with new glass compositions. One prime example is Venetian glass from the sixteenth through nineteenth century when glassworkers were attempting to create *cristallo*, glass with the clarity of rock crystal. In the process they overpurified the ingredients, lowered the amount of stabilizers, primarily lime (CaO), and increased the alkali content. The resulting glass melt was easy to work with at lower temperatures and produced brighter and completely colorless glass, but unfortunately it is also less durable.

In the past, this type of deterioration was commonly known as glass disease, although that term has fallen out of favor recently. Crizzling and weeping have also been used to describe the phenomenon, but they more accurately describe the symptoms at various stages of the deterioration process.

SEE ALSO: Conservation of Vitreous Materials; Glass and Faience

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Deterioration of Waterlogged Materials

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Waterlogged materials often enhance knowledge of the past by providing spectacular preservation of materials not normally found at archaeological sites. Deterioration of waterlogged materials occurs in the matrix of archaeological sites (and during use prior to deposition), accelerates when removed from the waterlogged matrix, and continues during study and after professional preservation. The ability to study waterlogged materials presents problems because they deteriorate rapidly when they are removed from their context. Salt-waterlogged materials add additional deterioration issues. Wood, cloth, low-fired pottery, metal, and other materials deteriorate in different ways, sometimes precluding their study until they are conserved because the surface is altered. Long-term conservation of waterlogged materials presents additional questions so that decisions often are made to select a small percentage of artifacts, beyond initial study, for conservation. The goal of conservation is to make the objects chemically stable for study, curation, and exhibit. Three-dimensional (3D) imaging using surface scanners or computed tomography (CT) machines provides a digital record of waterlogged objects when they continue to deteriorate (McKillop 2016).

Deterioration of waterlogged materials at sites

The preservation of specific kinds of materials and their deterioration vary according to the environmental setting of the waterlogged site. Northern European freshwater peat bogs provide a cool, acidic environmental setting where the tannic acid preserves human bodies. Freshwater

peat bogs in England preserved wood, such as the Bronze Age wooden posts and other wooden artifacts at the Must Have Farm site. Salt-water peat bogs in the tropics, such as the Paynes Creek Salt Works in southern Belize (McKillop 2005), preserve wood and other plant materials, but not bone, due to the acidic peat created by red mangroves (*Rhizophora mangle*). Mudslides such as at the Ozette site in Washington state, the United States, have preserved wood and basketry but not bone. Little decay of organic material occurred at the Windover site, where burials were placed 8,000–5,000 years ago, including textiles, wood stakes, gourds, bones, and shell preserved in the peat matrix of the base of the pond (Doran 2002). Wood, bone, and metal preserved in shipwrecks deteriorate in the water and further decay once removed to the air. Waterlogged wood exposed to oxygen at underwater sites decays by boring organisms such as worms.

Wood in wet sites, peat bogs, and underwater deteriorates. There are various stages of decay while the wood remains in situ, identified by the percentage of water in the wood. Over 200 percent water is considered degraded wood. Decay is recorded as class 1, with over 400 percent water, class 2, with 185–400 percent water, and class 3, with less than 185 percent water. As wood decays at wet archaeological sites, there is a sequence of loss of starch, sugars, mineral salts, color, and tannins, leaving the cellulose to support the wood structure. With further decay, the cellulose structure is lost, leaving lignin and water to retain the shape of the wood object, as long as it remains in water. If waterlogged objects removed from sites are allowed to dry, the cell walls collapse, causing shrinkage and warping, and even decay into dust in the absence of cellulose and lignin.

Deterioration of waterlogged materials during excavation

Waterlogged materials deteriorate during excavation if the preserving matrix is removed. Wooden

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buildings, as well as wooden objects and basketry were preserved by a mudslide at the Ozette site, but once exposed the wood began to dry and warp. The coffer dam constructed around La Salle's ship *La Belle* in the Gulf of Mexico to enable excavation contributed to deterioration of the ship by exposing the wood to the air, requiring constant flushing with water (Bruseth and Turner 2005).

Painted decoration on pottery in waterlogged settings can be altered by chemicals in the sediment matrix, such as sulfur. Permanently waterlogged pottery from Wild Cane Cay, an island trading port in southern Belize, was discolored, but the painted decorations were visible, albeit in shades of gray. Calcite-tempered pottery of Warrie Red type was discolored at underwater sites in a salt-water lagoon in Belize (McKillop 2002, 77–86). Original paint color also can permanently disappear quickly with exposure to air, so photo-documentation of any painted pottery or paint on other waterlogged objects, either in permanently waterlogged conditions on land sites or at underwater sites, needs to be carried out. The original color will not appear if the object is immersed in water.

Deterioration of materials during study and preservation

The *Mary Rose* ship was initially conserved by continuously spraying a solution of polyethylene glycol (PEG) at maximum 50 percent with a biocide to hinder biological decay for 20 years (Walsh et al. 2014). The researchers found that acidic salts and iron were able to permeate the wood with PEG conservation. Additionally, PEG can deteriorate to acids over time due to humidity, temperature, bacteria, iron, and natural acids. Polymer preservation is an advance over PEG since the polymer maintains wood integrity, does not decay into acids, and is inexpensive (Smith 2003). Two polymers, guar and chitosan (a biological inhibitor), were used to inhibit acidic and biological decay and prevent deterioration of wooden objects during preservation (Walsh et al. 2014).

Wood, leather, and other organic objects can be saturated with a 10 percent solution of PEG (which prevents the formation of ice crystals that expand and crack the cell walls when the object is frozen), frozen, and then put into a freeze-drier to preserve them long term, although they must be stored in humidity-controlled environments (45–60%). Preservation using the polymer process has been used on wood, china, metal, rope, paper, beads, basketry, and textiles from *La Belle*, with the wooden hull preserved using PEG (Bruseth and Turner 2005). The polymer process does not require humidity or temperature controls and the surface texture and color resemble the original, which is an advantage for display, but the process is not reversible (Smith 2003). Deterioration of waterlogged materials can be slowed by storing them in water. However, the water can contribute to deterioration by increasing the water content within porous materials such as wood. Water fills the inside of cells in the wood structure, softens the wood, and makes the wood subject to exfoliation of the surface, bloating, and fragmentation of the object due to weakness of the wood structure. Waterlogged wooden posts from the Paynes Creek Salt Works stored in water to desalinate them and maintain wood structure for 3D imaging and species identification became bloated and soft, obscuring surface details of the cut ends of the posts.

Deterioration can be slowed by wrapping waterlogged wood in plastic wrap and refrigerating the sample. Deterioration of waterlogged materials can continue after they have been conserved due to cracks or other deterioration that occurred during their usable life. For example, the K'ak' Naab' Maya canoe paddle continues to deteriorate due to cracks in the paddle in antiquity owing to its location in an alternating wet and dry landscape (McKillop 2005).

Waterlogged materials

Iron, copper, brass, and bronze objects corrode in seawater, obscuring the original surface of the item, and further decay from sulfate-reducing bacteria in seawater. X-rays of corroded metals can reveal the outline shape of the original object. If the metal item has completely corroded, a cast

can be made from the interior void space. If the metal is partially corroded, corrosion can be removed by electrolytic conversion (Bruseth and Turner 2005, 132).

Waterlogged wood has the internal cells and other spaces filled with water. Biodegrading by fungi and bacteria is slowed in waterlogged contexts, in contrast to the rapid decay at terrestrial sites. Underwater and terrestrial wet sites vary in the way they deteriorate archaeological materials according to the physical matrix of the site (open water, mangrove peat bog, or land/marine interface, for example), the geochemistry (sulfur, pH values), and available oxygen. Dissolved oxygen in water is reduced in stationary sediment, but increases with water flow, bioturbation, wave action, and disturbance by animals or people (Gregory 1998). Highly organic sediments, such as peat bogs and salt marshes, become anoxic within a few centimeters of the ground surface, significantly reducing oxygen flow and deterioration. Salinity levels influence what microorganisms are present at sites.

Deterioration of salt-waterlogged material

Salt-waterlogged objects deteriorate when allowed to air dry because the salt moves to the surface of the object, crystallizes and expands, cracks, and exfoliates the surface. Salt-waterlogged objects need to be desalinated by immersing them in freshwater to remove the salt. In low-fired pottery typical of many archaeological sites, once the salt has been removed, the pottery can be allowed to dry and the surface will be intact. Salt-waterlogged wood also needs to be desalinated by immersing the object or ship in water, and changing the water until it is fresh. Desalination time depends on the density and size of each object, but is generally a lengthy endeavor, taking months or years. Desalinated waterlogged wood will rapidly deteriorate if removed from water, resulting in changes to the wood structure, with internal cracks and collapse of cell walls, making microscopic species identification difficult or not possible, as well as shrinking and warping of the wooden object. Salt water deteriorates glass and metal artifacts.

Deterioration of waterlogged material returned to sites

Returning waterlogged finds to their origin site and covering them with sand bags, sediment, or plastic in order to recreate the anaerobic environment is a common solution for long-term preservation. If the reburial matrix is not anaerobic, decay of the waterlogged organic material occurs. Oak timbers (*Quercus virginiana*) stored for 50 years in freshwater had 4 percent loss in specific gravity, which translates as loss of strength of the wood (Winandy 1984).

Deterioration of waterlogged materials can be slowed by returning them to a matrix similar to their recovery conditions underwater. Pottery from the Paynes Creek Salt Works was cached in deep anaerobic silt underwater conditions after brief study and 3D imaging, with periodic checks indicating the low-fired pottery maintains its surface integrity.

Planning for excavation of waterlogged materials

A plan for study and disposition of waterlogged objects, buildings, and ships should be made prior to removal of waterlogged remains during survey or excavation. This includes consideration of short-term conservation for study as well as long-term conservation needs. Short-term conservation may be containerizing waterlogged objects in water for study, 3D imaging, and sampling. Long-term conservation may include returning objects to an underwater location or professional preservation by polymer (Smith 2003), freeze-drying (Walsh et al. 2014), PEG (Bruseth and Turner 2005), or refrigeration. Long-term conservation may include 3D digital imaging of the objects to maintain an accurate digital record, even if the original continues to deteriorate after professional preservation due to cracks or other conditions in antiquity. Long-term immersion in water will result in deterioration after a few years.

SEE ALSO: Charcoal and Wood Analysis; Conservation of Waterlogged Materials; Deterioration of Wood; Marine Excavation; Peat

Deposits; Polymers in Conservation; Structured Light Scanning

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Deterioration of Wood

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Introduction

Wooden artifacts and structures contain information about cultural and natural history at all levels, from the overall form to the microstructures. The receptivity of wood to deterioration is determined by the chemical, physical, and biological factors of the wood and of agents of deterioration in dynamic relationships. Knowledge of wood and the factors that influence and threaten it is essential to effective and ethical stewardship. The basic characteristics of wood and of the primary agents of deterioration and examples of common forms of ancient and historic preserved wood are presented here with the goal of providing a foundation for further study. There is a wealth of excellent resources available and I am in debt to those authors.

Wood

The two major taxonomic categories of trees are angiosperms referred to as hardwood and gymnosperms or softwoods. Angiosperms are broadleaf and produce flowers for pollination and are much larger and diverse taxa than gymnosperms that have needles and produce cones. Wood of both hardwoods and softwoods is the secondary xylem tissue that makes up approximately 70–93 percent of the biomass of a tree, with bast, bark, needles, and leaves making up the rest. Wood is primarily structural and provides transportation of water and nutrients. It grows inward from the cambium layer as phloem and bark grows outward. Cells are oriented longitudinally and radially, and wood structure is described using longitudinal, transverse, and tangential axes (Nilsson and Rowell 2012).

Wood cells differ seasonally, creating radial ring patterns which in temperate climates create annular rings. Older wood on the interior of the trunk ceases to function in transport and becomes denser and concentrated with extractives. This “heartwood” is usually more durable than the outer less dense “sapwood” and may be darker colored. Sapwood has a higher shrinkage rate when dried and is generally more vulnerable to microbes.

Wood is a biopolymer composed of three primary compounds—two polysaccharides, cellulose and hemicellulose, and the phenolic polymer lignin—and less than 10 percent non-structural compounds and extractives. These include pectin, tannins, terpenes, fatty acids, resins, and minerals. Pectin is present in cell walls, and extractives may impart color and odor and affect the durability of wood, but are not considered significant in evaluating agents of deterioration (Nilsson and Rowell 2012; Fanelli et al. 2008; Unger, Unger, and Schniewind 2001).

Cellulose comprises 40–45 percent of wood biomass. Parallel polysaccharide chains create microfibrils that group into fibrils that make wood fibers. Crystalline zones of microfibrils cause birefringence when observed microscopically (Fanelli et al. 2008). Hemicellulose, made of shorter polysaccharide chains, comprises approximately 35 percent of hardwoods and 20 percent of softwoods. Deterioration results from acid hydrolysis leading to decomposition, and specific microbial enzymes (Fanelli et al. 2008).

Lignins make up approximately 35 percent of softwoods and 25 percent of hardwoods. They are resistant to hydrolysis and sulfuric acid, but are broken down by oxidizing enzymes. Syringyl lignin in hardwoods is preferentially degraded by fungi (Unger et al. 2001; Berti, Palanti, and Pinzari 2008).

Wood cells have a primary outer lignin and hemicellulose wall, a three-layer secondary wall of cellulose and lignin, and around the lumen is a cellulose and hemicellulose layer. Wood cells are adhered together by pectin and lignins of the middle lamella (Berti et al. 2008). Specialized

architecture of wood tissue facilitates mechanical and transport functions. The chemistry of cellular features differs in vulnerability to chemical and microbial attack (Blanchette 2000).

Agents of deterioration

Risk is determined by the chemical, physical, and biological factors of the wood and of agents of deterioration in dynamic relationships. Pinna and Salvadori (2008) identify primary, secondary, and tertiary stages of bioreceptivity to describe how each phase creates the conditions for subsequent systems of deterioration. Increasingly refined analytical methods are being applied to determining mechanisms of deterioration and quantifying changes in wood.

Weathering

Discoloration, loss of surface cohesion and lifting fibers, warping, and cracking of weathering result from various impacts, including oxidation by ultraviolet light, acid hydrolysis by pollutants, and swelling and shrinkage and salt efflorescence cycles with atmospheric moisture (Unger et al. 2001; Catelli, Bănică, and Bănică 2016).

Fungi and bacteria

Microbial attack on wood in terrestrial climates is primarily from fungi and to a lesser extent bacteria. Submerged waterlogged wood in anaerobic environments is at risk from bacteria. Differences in microbial specialization, the chemistry and structures of the wood, and the environment will determine the type and nature of the degradation. Available moisture is a critical factor for microbe growth and a standard measure is the fiber saturation point—the amount of moisture present to saturate the cell wall plus some free water in the lumen (Unger et al. 2001; Blanchette 2000; Singh 2010).

Three categories of fungi are described by the visual characteristics at advanced stages of decay: white, brown, and soft rots. White and brown rot are caused primarily by basidiomycetes, of which there are thousands of species. White rot

targets lignin, causing blanching and deterioration of the middle lamella (Berti et al. 2008; Blanchette 2000). Detection may be delayed because wood retains its structure into later stages of deterioration. Brown rot attacks cellulose and hemicellulose and causes degradation of cell walls. Remaining dark lignin-rich wood cracks into a cubical pattern when dry. Loss of strength occurs early in the deterioration process. Brown rot, also called dry rot, is caused by *Serpula lacrymans*, which can remain active at relative humidity as low as 22 percent (Berti et al. 2008). Brown and white rot are optimized at water content between 40 and 80 percent of oven dry weight. Water content below 20 percent is recommended to protect wooden artifacts (Blanchette 2000).

Soft rot is primarily caused by ascomycetes fungi. These are slower acting than white or brown rot but tolerate higher moisture, alkaline pH, some preservatives, and low oxygen levels. Consequently, soft rot attacks waterlogged or damp wood. Two types of soft rot are distinguished. The first attacks carbohydrates but not lignin of hardwoods (angiosperms) and the middle lamella is retained or modified. Type two attacks polysaccharides of softwoods (gymnosperm), destroying the secondary wall but leaving lignin. Both reduce structural strength. Some basidiomycetes and ascomycetes cause only chromatic alterations but increase the hygroscopicity and therefore attract other microbial degradation (Unger et al. 2001; Berti et al. 2008).

Several groups of bacterial microbes that require high moisture content and are tolerant of low oxygen and anaerobic environments are active on waterlogged wood and wood in waterlogged soil. They break down cellulose and are associated with three types of microscopic deterioration: erosion, cavitation, and tunneling (Berti et al. 2008; Singh 2010; Reinprecht 2016).

Insects

Insect pests consume, excavate, and inhabit wood and are the primary animal agents of deterioration of terrestrial wood. The three most wood-damaging insects are hymenoptera, and two xylophageous or wood-eating beetles (Coleoptera) and termites (Isoptera). But there

are many insect species that damage wood, and attack may come from insects in other adjacent materials, such as dermestids that consume protein but infest previously decayed wood for pupation (Unger et al. 2001; Ilbach 2013).

Insect larval stages are the primary agents of destruction, though adults may also cause damage. Differences in the wood that is attacked and the type of damage varies with insect species and is determined by nutritional and reproductive needs, environmental conditions, whether the wood is a hard or softwood, and what species. Some species may require gut microbes to digest components of wood, have symbiotic relationships with fungi, or have restricted tolerance for temperature and moisture. Knowledge of these factors is critical to effective treatment; for example, heat treatment that denatures proteins required by house longhorn beetle (*Hylotrupes bajulus*) will not be effective on powderpost beetles (hycidae) that do not require protein (Unger et al. 2001; Reinprecht 2016). The discovery of insects, sawdust, or frass requires immediate attention to identify the insect, and determine and instigate the appropriate eradication method (Unger et al. 2001; Reinprecht 2016).

Other agents of deterioration

Wood-boring shipworms, the bivalve Teredinidae and the crustacean *Limnoria lignorum*, cause damage to submerged wood in marine environments, depending on the salinity and temperature of the water. Both attack hard and soft woods (Unger et al. 2001; Ilbach 2013). Many terrestrial animals cause damage and deterioration of wood through mechanical action and introduction of chemical agents as urine and food.

Archaeological and historic wood

Historic wooden heritage objects and archaeological wood have been preserved or partially preserved in desiccated, anaerobic, and frozen environments that constrained agents of deterioration (Nilsson and Rowell 2012; Matthiesen et al. 2014).

Desiccated wood

The best-preserved wooden artifacts have been found in arid conditions where the moisture content remained consistently below 20 percent, and therefore too low for sustained microbial attack, and the wood was protected from insect pests. Studies by Nilsson and Daniel identified microscopic degradation of the cellulose and weakening of microstructures, while the overall structure remained intact (Nilsson and Rowell 2012; Unger et al. 2001).

Waterlogged wood

Important waterlogged wooden heritage objects have been partially preserved in anaerobic marine and freshwater environments, and in saturated soil and silt. Fungal and microbial action is constrained, but cellulose and hemicellulose are eroded by hydrolysis, and anaerobic reducing bacteria attack lignin, reducing mass and structural strength (Florian 1990; Blanchette 2000). While submerged water replaces lost material and supports the structure, removal of the artifact causes catastrophic collapse unless the water is gradually replaced by a consolidant in complex conservation treatment.

Summary

Knowledge of structures and agents and mechanisms of deterioration is essential to the ethical and effective stewardship of wooden heritage objects. This overview is a foundation for research to determine conservation practices that will preserve the information latent within the structures and chemistry of wood.

SEE ALSO: Archaeoentomology;
Bioarchaeology; Charcoal and Wood Analysis;
Conservation of Waterlogged Materials;
Deterioration of Waterlogged Materials; Material Culture

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Electron Microscopy in Conservation

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Brief history of microscopy

Conservation science addresses issues related to the protection and preservation of heritage materials, including works of art and architecture, and archaeological and historical artifacts. To a great extent, it relies on the evidence presented by the scientific tools employed in the analysis. Microscopy is among the most important techniques to address research needs. A microscope can be defined as a tool that transforms an object into an image, and as a result of such transformation we are able to see the smallest details of the object. *Resolution* is the smallest distance between two points on a specimen that can be observed as separate entities. The resolution of the human eye is generally accepted to be close to 0.1–0.2 mm and any tool that allows us to resolve smaller details can be classified as “a microscope.”

The simplest device which extends our ability to see details beyond eye resolution is a glass lens. Lenses are known to have been used by humans for thousands of years. The oldest known were used by ancient Egyptians and were made of natural crystals. The optical microscope, or “light microscope,” uses visible light and a system of glass lenses to magnify the object. These are the oldest and simplest of microscopes. Though under dispute whom to consider as the inventor of the light microscope, it is accepted that in the seventeenth century a Dutch engineer and craftsman, Antonie Van Leeuwenhoek, was the first to use a microscope as a scientific tool (Dobell 1958). He observed plants and small animals under the microscope and published his observations in scientific journals. Since then, light microscopy has significantly developed,

with improved resolution mostly by perfecting the quality of the glass lenses.

However, in the mid-nineteenth century, due to development of the wave theory of light, it was realized that the resolution of optical microscopy is limited by diffraction. Its physical limit is summarized by the Rayleigh criterion, which states that resolution is related to the *wavelength* of visible light: Resolution is higher (better) when the wavelength is shorter (Rayleigh 1879). Since the wavelength of visible light is roughly in the range 400–700 nm of the electromagnetic spectrum, it was recognized that the physical limit of light microscopy is somewhere around 200–300 nm. This triggered the search for a different type of microscopy that could surpass the resolution limit of light systems. Towards this goal, one of the greatest discoveries was made by the French physicist Louis de Broglie at the beginning of the twentieth century. His theory suggested that an electron has wave-like properties and its wavelength can be controlled by accelerating the voltage the electron travels through. This discovery revolutionized the field of microscopy, since it was recognized that the wavelength of an electron can be about five orders of magnitude shorter than the wavelength of visible light, allowing resolution capability far below the size of an individual atom.

One of the problems in using electrons instead of light in microscopy is that regular glass lenses cannot be used to control the electrons. However, the famous Lorentz equation addressed this concern, showing that electric or magnetic fields could be used instead. Thus, the idea of using magnetic lenses to focus high-energy beams of electrons did not take long to put into practice. In 1931, two German physicists and engineers, Ernst Ruska and Max Knoll, invented the first *transmission electron microscope* (TEM). The development of the *scanning electron microscope* (SEM) in 1942 by US engineer Vladimir Zworykin was related to the invention of the TV signal processing, which is principally different from the optical signal used in TEM. A fundamental discovery made by British chemist Henry Moseley in 1913 showed that the energy of emitted characteristic

X-ray radiation produced by a specimen exposed to a high-energy electron beam is a function of the atomic number of the emitting element. This discovery led to the technique of X-ray spectrochemical analysis, by which elements present in a specimen could be identified by their characteristic X-ray energies. The first electron microscope suitable for elemental analysis was built in 1949 by Raimond Castaing and André Guinier.

Basic principles of electron microscopy

Electron microscopy (EM) applies a high-energy electron beam. When electrons interact with the sample they get scattered and are capable of *ionizing* the matter's atom, that is, of removing the inner-shell electron from the attractive field of the nucleus. As a consequence of electron scattering, the specimen produces different signals in EM. These include: *secondary electrons* (SE); *backscattered electrons* (BSE); *characteristic X-rays*; *Auger electrons*; *cathodoluminescence* (CL); specimen current; and Bremsstrahlung X-ray. All these signals are generated simultaneously, but require specialized detectors. SE signal is generated by the electrons that are initially part of the specimen but got knocked out as a result of scattering. BSE results from multiple elastic scatterings of the primary electrons by the specimen. Energies of SE and BSE are not specific for the specimen's atoms, and signals are only used for imaging purposes. Signals are defined by their energies: SE are bound to the energy range of 0–50 eV, and BSE are 50 eV and up to E_0 , where E_0 is the accelerating voltage EM uses. Due to the big difference in their energies these signals can give distinctively different types of images. Characteristic X-rays are produced by the atom of the specimen as a result of bringing the atom to the ground state after one of its inner-shell electrons got knocked from its orbit by the high-energy beam electron. Auger electrons emission is an alternative (to X-ray) way of relaxation of a specimen's atom: The atom can emit its outer-shell electron (Auger) instead of the characteristic X-ray photon.

Characteristic X-ray and Auger electron signals carry very specific energies that represent the scattering atom of the specimen, and that is why

they are primarily used for elemental chemical analysis. Characteristic X-ray and Auger electron emission are related. The probability of Auger electron emission is higher for light elements contrary to X-ray emission, and vice versa for heavy elements. This makes Auger spectroscopy one of the most powerful techniques for the detection of light elements, and X-ray signal techniques for medium and heavy elements. There are two different methods in EM that make use of the characteristic X-ray signal: energy-dispersive spectroscopy (EDS) and wavelength-dispersive spectroscopy (WDS). These are different in terms of the X-ray signal detection and processing and provide different accuracy and sensitivity for element detection (Goldstein et al. 1992). CL is a signal of light produced by the specimen as a result of its bombardment by high-energy beam electrons. The wavelength of emitted light depends on the band-gap size of the material, and its measurement can address band-gap value-related problems in materials. The specimen's current signal distinguishes areas on the specimen with different conductivity.

Except for the Bremsstrahlung X-ray (background on X-ray spectra), all of the signals have useful applications in different types of EM. TEM mostly uses nonscattered (transmitted) and elastically scattered (diffracted) electrons. SEM mostly uses SE, BSE, and characteristic X-ray signals. All other signals, including Auger electrons and CL, require a more specialized system design, but the instruments which use these signals also belong to the class of EMs where the high-energy electron beam is used as a primary source.

EMs are highly regarded scientific tools since they can provide data on topography and morphology of the specimen at resolutions much higher than light microscopes: commonly, a few nanometers in SEM and a few angstroms (or better) in TEM. EMs can also provide information on the crystal structure and elemental composition of the specimen, not achievable with the light microscope. SEM can be considered as a scientific tool suitable to image the external structure of a specimen, and TEM, the internal structure.

Although TEM and SEM are both electron microscopes, they operate by different principles. Their major difference is based on the type of image formation they use and it determines the way we magnify the object, and calculate the

resolution and depth of field, and some other important characteristics. TEM uses lenses to magnify an object. This type of image formation is called *optical*. In this respect, TEM is very similar to the light microscope; the only difference is that it uses magnetic lenses instead of glass lenses. Furthermore, it requires the specimen to be transparent for the electrons, and therefore samples need to be very thin (~100 nm). The image contrast is formed due to the difference in electron scattering by different areas on the specimen. The areas on the sample that scatter more strongly will appear darker in the image. This mechanism is called *mass-thickness contrast* and it is the most commonly used contrast mechanism in TEM.

Two other contrast mechanisms exist in TEM: diffraction contrast and phase contrast. These are more important particularly for the crystalline materials and when TEM operates at very high magnifications. TEM is the perfect tool when high resolution is required, and it can solve different problems related to crystallography since it allows collection and study of electron diffraction routinely. TEMs can be equipped with EDS systems for chemical analysis. However, TEM requires microsamples (normally 3-mm disks), which can pose challenges in the analysis of archaeological materials, as sampling could be a limiting factor.

SEM utilizes a *scanning* type of image formation. The image is formed by individual pixels (picture elements), which are formed at different time intervals. In an electron scanning image, a high-energy electron beam moves across a small rectangular area on the specimen with changing x and y coordinates on the specimen, creating a raster. Each pixel of the object generates all varieties of signals, which can be collected by the specialized detectors. Collected signal modulates the intensity of the pixel on the cathode ray tube or a computer monitor. The x, y position of the pixel on the monitor and on the specimen's raster is correlated so that the beam motion over the sample and the pixel's reading on the monitor are synchronized. Due to the high frequency of the scanning (50 frames per second in TV mode), the image appears to the human eye as formed instantly. It becomes evident that the scanning type of image does not need lenses to magnify the object. Magnification in SEM is determined by the ratio between the size of the monitor used and the raster applied on the specimen. However,

SEM uses magnetic lenses to focus the electron beam (demagnify its size) on the sample, forming a small-size probe. Probe size determines the spatial resolution of SEM.

One of the most important characteristics of the scanning type of image formation is the very high *depth of field* compared to the optical image, which is often valued—even higher than a good spatial resolution. As a result, the sample can be studied in SEM without having been polished flat. The most important signals which are used for imaging in SEM are SE and BSE. Both signals' intensities are directly related to the local tilt of the specimen toward the electron beam: The higher the tilt, the stronger the yield of both SE and BSE. This is a major mechanism for *topographic contrast* that can be formed with both signals. In addition, the yield of BSE depends on the average atomic number (Z) of the area on the specimen analyzed and it is stronger when Z is higher. This makes it possible to observe *compositional contrast* with BSE. The coupling of EDS or WDS with SEM enables simultaneous elemental analysis of the sample. It is important to note that due to the different principles these two techniques use, the limit of detection and the energy resolution (ability to distinguish between elements with very similar energies) are very distinct. In optimal experimental settings (flat polished surface of the specimen, adequate beam current and X-ray signal) the limit of detection of EDS is about 0.1 wt%, whereas in WDS it is about 0.01 wt%. Due to its excellent energy resolution, WDS is capable of distinguishing signals from all elements, whereas EDS very often is incapable of doing this. For example, Pb, Mo, and S (respective M, L, and K photon emissions) are nondistinguishable with EDS. In SEM the distribution of the chemical elements across the sample surface can be mapped and correlated to the electron topographic or compositional contrast images. Spatial resolution of EDS in SEM is generally accepted as approximately 1 μm , whereas in TEM it is about two to three orders of magnitude better. Currently, SEMs are routinely equipped with an *electron backscatter diffraction detector* (EBSD), which allows the measuring of crystallinity of the specimen within a few tens of nanometers.

One of the most important advancements in SEM is the use of differential pumping systems

and a series of pressure-limiting apertures which allows SEM to operate at variable pressure (VP) (50–300 Pa) or environmental (E) pressure (up to 900 Pa), while the electron gun compartment is at very low pressure (10^{-5} Pa and better). These SEMs allow charge neutralization on the specimen and do not require the specimen to be conductive. They also allow for dynamic studies by changing the environmental conditions in the chamber (Stulik and Doehne 1991). Large SEM chambers also enable the study of big specimens or entire objects (70 cm in diameter and 300 kg in weight) (Mayer et al. 2007). Finally, recent progress in electron optics and electron source (field emission guns) design makes modern SEM an extremely versatile and powerful tool capable of studying heritage objects nondestructively and often noninvasively.

New developments in integrating different technologies led to the revolutionary coupling of a VP-SEM with Raman spectromicroscopy (μ RS). The coupling of the VP-SEM with EDS and μ RS unites three well-established technologies in a novel interfaced system. It takes full advantage of the high spatial resolution offered by the VP-SEM for nondestructive in-situ submicron morphological and topographic mapping, and the atomic and molecular microprobing of the EDS and μ RS for simultaneous spatially resolved elemental composition and chemical speciation of materials.

EM applications in conservation

Scientific studies to understand ancient technology and materials' degradation are very important components in heritage conservation. Understanding the make-up of objects and assessing degradation is vital to inform conservation decisions and treatments. By combining the imaging and analytical capabilities of the different detectors (SE, BSE, and EDS), crucial information can be obtained from microscopic specimens for answering important questions related to an artistic technique or the state of preservation of an artifact (Barabe 2003; Ciliberto and Spoto 2000). As many heritage materials are nonconductive (or could dehydrate or outgas in high vacuum), VP-SEMs provide a suitable

alternative to high-vacuum systems. This technology enables the analysis of small specimens without modification to their chemistry and structure (Prikhodko et al. 2007).

E-SEMs can further enable dynamic studies of materials to monitor phase transformations and weathering in real time, by modifying the environmental parameters in the SEM chamber. This was demonstrated by dynamic experiments on stone preservation affected by salts (Baker, Uwins, and Mackinnon 1993; Doehne 2006). Another preservation-related challenge often encountered by conservation scientists that could be facilitated using E-SEM is finding the optimum range of relative humidity and temperature for the long-term preservation of artifacts (Doehne and Baken 2006).

The coupling of VP-SEM with EDS and μ RS has offered new capabilities for noninvasive and minimally invasive analysis of heritage materials. Using a VP-SEM-EDS- μ RS system, questions requiring topographical and compositional contrast, and elemental and chemical composition can be answered without having to move the specimen/object and without the need to coat the samples (Prikhodko et al. 2015).

It is important to emphasize that EM provides nondestructive analysis, as it does not consume the sample to yield results. In this respect it can complement some other traditional methods used in conservation, for instance polarized light microscopy, portable XRF, and Raman and infrared spectroscopy. An advantage is that the same samples analyzed using SEM can be further analyzed by some other common techniques. This helps maximize the information obtained from the study of objects to inform conservation decisions.

SEE ALSO: Electron Backscatter Diffraction (EBSD); Optical Microscopy; Raman Spectroscopy; Raman Spectroscopy and Material Analysis; Raman Spectroscopy in Conservation; Transmission Electron Microscopy

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Grouting in Conservation

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Grouting is an intervention method intended to restore the continuity of elements, such as walls, plasters (see CONSERVATION OF POLYCHROME NATURAL AND ARCHITECTURAL SURFACES), wall paintings, mosaics (see CONSERVATION OF MOSAICS) (see Figure 1a), and stone ornaments (see CONSERVATION OF STONE AND PETROGLYPHS), in the context of archeological sites, historic buildings, and monuments, by readhering detached areas or elements and filling voids and cracks that are inaccessible or difficult to access from the surface. While sometimes used interchangeably in the literature, it is important to emphasize that, as an intervention method, grouting differs from consolidation (see MINERAL INORGANIC TREATMENTS and POLYMERS IN CONSERVATION), which intends to reestablish cohesion of materials (stone, bricks, mortars, etc.) that have lost their binder.

Grouting applications for conservation can be grouped under structural and nonstructural grouting based on their function. Structural grouting aims to fill cracks and voids within the wall core or separation between the leafs of a masonry wall. Structural grouting is suitable when cracks and voids in the wall could cause structural instability and problems of water infiltration. Nonstructural grouting addresses voids and cracks in architectural surfaces. It aims to reestablish adhesion between delaminated layers of stone, plasters, wall paintings, and mosaics, or between these layers and the substrate.

Methodology

A systematic and well-defined condition assessment is crucial to identify conservation issues, and to determine if grouting is the most suitable intervention method for the specific case.

In some cases pinning with dowels, anchoring, or tie-bars may be used, and these techniques have been used in the past to reestablish the connection between wall leafs or between layers of architectural surfaces or architectural surfaces and substrate. Surface delamination can sometimes be repaired using a compatible mortar fill. It should be noted that grouting is an irreversible intervention, and retreatability can be challenging, particularly if a previous grouting intervention prevents the entrance of new grout. Additionally, grouting involves drilling holes on the surface to access voids, which leads to permanent damage of the historic fabric. Most of the time existing surface cracks can be used as injection points to minimize the damage, especially for decorated surfaces where the surface is of great value.

The focus of the condition assessment is to identify the condition of existing materials (both original materials and repairs), understand the past and current exposure conditions, document and map deterioration (see DETERIORATION) symptoms, and understand the related deterioration mechanisms, combined with material analysis to characterize original materials (e.g., plaster, stone, brick).

A variety of nondestructive, minimally destructive, or in some cases destructive diagnostic tools can be used for the condition survey in the field and laboratory. To detect delaminations and voids behind the surface, techniques include percussive tapping, infrared thermography (see THERMOGRAPHY), endoscopy or fiber optic probe, laser speckle interferometry (electronic speckle pattern interferometry (ESPI) or TV-holography) (Hinsch et al. 2009), sonic tomography (Silva et al. 2014), and ground-penetrating radar (see GROUND-PENETRATING RADAR). Additionally, a number of analytical laboratory tests can be performed on collected samples (core samples (see CORING), powder, chips, etc.) to study the chemical, physical, and mechanical characteristics of the materials to be treated and to identify existing deterioration mechanisms. These include

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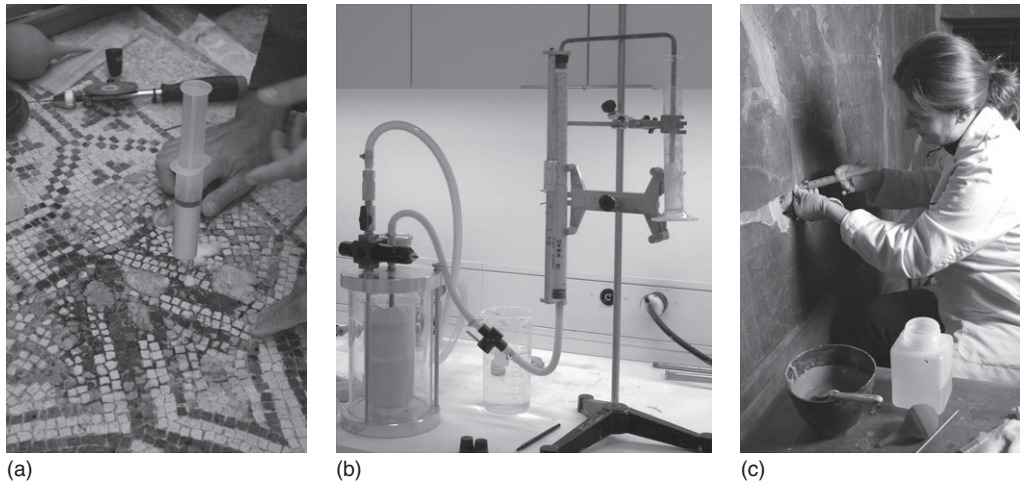


Figure 1 (a) Injecting grout into a floor mosaic to restore the continuity; (b) Testing the injectability of a grout. The grout is injected at constant pressure from the bottom of a vertically held column filled with granular material; (c) Grouting of a wall painting using a syringe.
Source: (a), (b) and (c) copyright © [2017] The J. Paul Getty Trust.

elemental analysis (e.g., X-ray fluorescence [XRF], see X-RAY FLUORESCENCE SPECTROMETRY (XRF)) and scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDS), compositional analysis (e.g., X-ray diffraction [XRD], see XRD AND MATERIALS ANALYSIS), thermogravimetric analysis–mass spectrometry (see MASS SPECTROMETRY (MS)), and petrography (see PETROGRAPHY AND CERAMICS), wet chemical analysis, sieve analysis, salt analysis (e.g., ion chromatography [IC], see CHROMATOGRAPHY AND ARCHAEOLOGICAL MATERIALS ANALYSIS), porosity, water absorption, vapor permeability, and strength measurements (Silva et al. 2014).

Based on the information collected during the condition assessment, the need for grouting, the desired properties of the grout, and the development or selection of a grout that will be compatible with the original materials for the specific case can be determined. These decisions should be made by an experienced interdisciplinary team including conservators, conservation scientists, conservation architects, and structural engineers. Since grouting is an irreversible intervention, the selection or development of an appropriate grout is crucial for the success of the intervention and to avoid the need for frequent repeated interventions.

Selection or design of a grout

A grout is a bulked fluid material including one or more binders (see CEMENTS, MORTARS, BINDERS), fillers (ultrafine or fine aggregate), liquid, and generally admixtures to control its fluidity. Due to compatibility concerns, water-based mineral grouts are commonly used and the use of polymer-based or other solvent-based (epoxy and polyester resin) grouts are not recommended. In the conservation field, both custom mixed and commercial proprietary grouts are used. With the general acceptance of preserving architectural surfaces in their original context, a number of commercial grouts have been developed for various uses (e.g., lightweight grouts, grouts for frescoes, etc.) since the 1980s. Custom-mixed grouts are typically designed for specific use on a case-by-case basis (Ferragni et al. 1984).

The required properties of a grout should be selected after considering the deterioration issues identified in the field (e.g., deep voids requiring low shrinkage grouts; voids in vaults and ceilings requiring lightweight grouts; fine cracks and thin delaminations requiring very fluid grouts) and the function of grout (structural or nonstructural).

In general, grouts should be compatible with the original materials (substrate and plasters). They should be fluid enough to be injected with no clogging and have minimal separation of components. The volume shrinkage of a grout (from wet paste to hardened solid) should be minimal. Additionally, the concentration of soluble salts in the grout should be as low as possible. The hydric transport properties (i.e., capillary water absorption and water vapor permeability) of the cured injection grout should be similar to that of the original material, and the cured grout should not create a vapor barrier. Following conservation principles, the mechanical properties (i.e., compressive, shear, or tensile strength, modulus of elasticity) of the cured injection grout should be similar to, but less than, the original plaster and substrate to avoid any damage to the original material under existing exposure conditions. Grouts should provide an adequate bond, and the bond strength at the interfaces should be similar to but less than the strength of the original materials. For cases where the aim of grouting is the strengthening or retrofitting of masonry structures, the effectiveness of grouting to fulfill this aim without developing extreme strength (mechanical or bond) and rigidity should be demonstrated. Finally, injected grouts should be sufficiently durable.

The properties of grouts that can be measured in the laboratory include expansion and bleeding, injectability (see Figure 1b), drying shrinkage, splitting tensile strength, soluble salt content, coefficient of capillary water absorption, water vapor permeability, wet and dry densities, shear or tensile bond strength, and resistance to salts or freeze-thaw. Since grouting has become a commonly used intervention method in conservation, research has focused on the development of appropriate testing methods and the development of a comprehensive and systematic evaluation of injection grouts both in the laboratory and field (Biçer-Şimşir and Rainer 2013; Jorne, Henriques, and Baltazar 2015).

Once one or more candidate grouts have been identified, they should be tested in the field prior to implementation. It is important to note that conditions in the field can differ from laboratory conditions, and may affect the performance of the grout. Following field trials, complications with the grouting process should be identified

and necessary precautions should be taken. If the performance of the grout is not satisfactory, modifications to custom-mixed grouts can be made and different commercial grouts can be tested.

Before grouting

Preparation of the area (wall, ceiling, vault, floor, etc.) to be grouted is critical to a successful grouting intervention. If necessary other interventions such as consolidation, desalination, or mortar repairs should be carried out before grouting. Debris, which has accumulated in voids, should be thoroughly cleaned out. For architectural surfaces, this may be done by aspiration using mini-vacuum attachments (e.g., computer vacuum attachments), air bulbs, and other small tools to empty cavities of debris. Often a hole must be made to access and empty debris. Water or preferably a water and alcohol (50:50) mixture can also be used to flush the cavity. Similarly, interior surfaces can be prewetted to facilitate passage of the injection grout through interior networks prior to grouting, to ensure adequate adhesion of the grout, and to avoid rapid drying. When liquids are used to flush or prewet, caution should be taken not to inject excess water in the void behind the surface, as it can dilute the grout mixture and modify its properties. The use of water to flush or prewet can also mobilize existing salts and lead to surface or subsurface efflorescence. Plant growth should be removed prior to grouting, as root systems might also prevent the grout from flowing properly. For structural grouting, a grid of injection ports can be prepared. In some instances, air holes may be drilled to facilitate passage of the grout. However, on most wall paintings, this is not advised, and typically, preexisting holes, cracks, or losses are used as injection ports when possible. For structural grouting or filling of large voids, a grid of application holes is drilled, but this is clearly not desirable for wall paintings' conservation. Holes through which the grout could leak, should be sealed to prevent grout from dripping onto the surface; fine cracks may be faced, and if necessary, the edges of the area to be treated can be sealed with materials such as plasticine, cyclododecane, or a mortar used for fills.

Grouting

Once one or more grouting areas have been prepared, the grout mixture is prepared and introduced. The most common grouting methods are gravity and pressure grouting. Application of vacuum grouting in conservation is very limited largely due to the need for extensive preparation (vacuuming out air and water) and issues of incompatibility with the use of low-viscosity resins. It should be kept in mind that grouting is a challenging procedure and should be undertaken by only experienced conservators and conservation professionals.

For nonstructural grouting, the technique utilized to introduce grout into the void depends upon the size, accessibility, and alignment of the void. If the void can be accessed from the top, then the grout can be introduced at the upper edge and allowed to flow down inside the void, using gravity grouting, which can also be used for floor mosaics. Otherwise, grout is usually injected by syringe with a cannula of appropriate size (Figure 1c). For especially large voids, transfusion tubing can also be used.

While gravity grouting is simpler in terms of equipment and application requirements, low-pressure pumping is usually the most appropriate method for structural grouting.

Both structural and nonstructural grouting starts at the base of the wall or void when possible. In the case of particularly large cavities, the grout should be applied in stages or lifts, to give each grout application sufficient time to lose water and become fairly dry and hard.

Frequently, and particularly in the case of fragile architectural surfaces and vaults, it may be necessary to hold the plaster, wall painting, or mosaic in place by the use of supports while grouting is being carried out and during setting. Applying pressure to the grouted area can, in some cases, also realign a deformed plaster and provide better contact and adhesion of the grout to the substrate and plaster layers.

During grouting, work should be monitored. The penetration of grouting can be monitored by nondestructive methods such as thermography and laser speckle interferometry as described above.

After grouting

Following grouting, the surface should be checked to ensure that no grout remains on the surface. Grout may flow and reappear on the surface in unexpected places and excess grout may discolor the surfaces on which it is deposited if it is not removed in a timely fashion.

Periodic post-treatment monitoring, using nondestructive diagnostic tools should be carried out to ensure the durability of the treatment over time and to identify new cracks, voids, and delaminations. An evaluation of the wall, plaster, wall painting or mosaic should also be carried out after a natural disaster such as seismic activity or any other event that could cause damage.

SEE ALSO: Chromatographic Techniques in Conservation; Conservation of Earthen Building Materials; Deterioration of Earthen Building Materials; Deterioration of Mosaics; Deterioration of Stone and Petroglyphs; Electron Microscopy in Conservation; X-Ray Fluorescence Spectrometry (XRF)

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FURTHER READINGS

Inpainting

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The noun *inpainting* is a prepositional compound with “in”: in + painting, that is, “painting inside.” It seems to have appeared in the conservation literature of the United States in 1935 (Metzger, Maines, and Dunn 2011), when it was proposed by G. L. Stout and described as “placement of new paint in the lacunae of the old film” (Stout 1935). Buck and Stout (1940) offered a definition of inpainting as “compensation of losses with no new paint put over that which is old and original,” thus avoiding arbitrary intervention, and distinguished it from overpainting which goes “beyond mere compensation in the area of loss.” This approach characterizes the modern profession of “conservator,” which was then being established in Europe and in the United States; conservators were replacing the outdated approach of the restorers of the previous generations, whose overpainting often obliterated and modified original parts of the painting. “Retouching,” a more widespread term, though older and less specific, describes the artist’s action of perfecting his or her painting with touches of color. In the United States more than in Europe, the term “inpainting” is preferred to retouching, because it speaks to the aim of modern conservation practice to introduce new ethical standards and techniques.

Compensation for losses has been a crucial point in all theoretical and ethical approaches to conservation (Hill Stoner and Rushfield 2012). The conservator may reduce the visual disruption caused by the loss or alteration of the original paint layers by adding color, either through mimetic (imitative) retouching or in a differentiated way. Being among the conclusive steps of a conservation treatment, inpainting is also the one that acts as mediator in the relationship

with the public and facilitates understanding of the painting. It is therefore not surprising that inpainting is often identified with the entire process, especially since to restore literally means to reinstate the missing parts of an object.

Pietro Edwards, chief restorer for the public paintings in Venice in the late eighteenth century, recommended the least possible amount of integration, mostly within the losses, and with varnish-bound colors that could be removed with no damage to the original painting. The instructions in his writings reveal a deep understanding of the realities of the process—an understanding that derives from his personal involvement in the treatment of paintings (Tranquilli 1996).

Imitative and interpretative overpainting prevailed until the beginning of the twentieth century, when a more rational and respectful approach was reinstated in the field of painting conservation. The International Conference for the Study of Scientific Methods for the Examination and Preservation of Works of Art, held in Rome in 1930, is considered to have been a seminal event for the establishment of the modern discipline of conservation (International Museums Office 1997). The subject of retouching held a central place in that discussion, identifying the distinction between the modern imitative techniques and the traditional “deceptive” ones. The importance was made clear of limiting the intervention to the areas of loss, working with reversible materials, and ensuring the recognition of inpainted areas through photographic documentation. At the Rome Conference Helmut Ruhemann (1968) proposed to work on differentiated retouching; but later on he went back to mimetic reintegration, as no method seemed satisfying.

Imitative inpainting is based on a long-standing tradition and its principles and development are empirical rather than based on philosophical reasoning. Indeed, imitative techniques are those most often used at an international level. Prioritizing the unified appreciation of the painting, they allow for the important element of the conservator’s subjectivity when facing the great variety of damages sustained by the original paint layer.

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The need for shared and structured principles has motivated the redaction of guidelines for ethics. In the Code of Ethics and Guidelines for Practice issued by the American Institute for Conservation, we read (https://www.nps.gov/training/tel/Guides/HPS1022_AIC_Code_of_Ethics.pdf):

Any intervention to compensate for loss should be documented in treatment records and reports and should be detectable by common examination methods. Such compensation should be reversible and should not falsely modify the known aesthetic, conceptual, and physical characteristics of the cultural property, especially by removing or obscuring original material. (23: Compensation for Loss)

The concept of “authenticity” is connected to that of “autography” and even to that of “truth”—notions that have always aroused respect and reverence. At the core of the debate in the history of restoration and conservation, the conflict between authenticity and unified appreciation of the artwork has seen solutions ranging from stylistic reinterpretation to archaeological presentation of autograph fragments of paint layers. Nevertheless, the definition of authenticity has changed over the centuries, moving away from the “competitive” approach of the Renaissance and baroque periods, when older works were reshaped so as to acquire new value instead of losing it. During the Enlightenment, the progressive application of the scientific method to all the fields of culture directed new attention to the original materials, as demonstrated in the work of Pietro Edwards. A contemporary definition of authenticity is expressed in the 1994 Nara Declaration on Authenticity (available on the UNESCO website, at <https://www.icomos.org/en/about-icomos/179-articles-en-francais/ressources/charters-and-standards/386-the-nara-document-on-authenticity-1994>). According to the Nara statement, the conservation of cultural heritage is rooted in the values attributed to heritage by the stakeholders. Values, and authenticity more than others, depend on the degree to which the information sources related to them are credible or truthful. Such evaluations may differ from culture to culture, and even within the same culture. It is thus not possible to

base judgments of value and authenticity on fixed criteria.

The Italian approach to the problem of authenticity versus the subjectivity of the conservator is grounded in the comprehensive theory of conservation developed by the art historian Cesare Brandi between the 1940s and the 1960s as he aimed to guide the treatment of losses through a philological and critical approach (Brandi [1963] 2005). His best known concept of a “theory of restoration” (*teoria del restauro*, Brandi [1963] 2005) is that of the recognizable integration of losses achieved through the *tratteggio verticale* (“vertical hatching”). Similar hatching techniques, such as the *selezione cromatica* (“chromatic selection”) and the *astrazione cromatica* (“chromatic abstraction”), were proposed in Florence by Umberto Baldini in the 1970s (Casazza 1981). The *teoria del restauro* was developed within the philosophical discipline of aesthetics and had important contributions from Gestalt psychology, namely regarding the ability of the human brain to visually integrate specific kinds of losses and to differentiate between the respective roles of image and background—which proved to be particularly useful for works of art built with a stratigraphic sequence of distinct layers. These considerations resulted in a reduction of the amount of integration of losses that was necessary in order to establish a correct balance between the aesthetic and the historical cases. The typological differentiation of losses according to their position in the stratigraphy—whether they affected intermediary layers of paint or only the uppermost pictorial surface—was a key element.

The choice that was considered to be the most respectful one was to treat the loss chromatically, in order to have it recede to a lower layer in the stratigraphy, thus reducing its perception by assimilating it into the background. A superficial paint loss can be assigned the perceptual value of an area where the preparatory layers, made visible by the lacuna, are easily interpreted as having that value. These areas looked clean and consistent and seemed to belong recognizably to a lower layer (with respect to color, surface texture, and level); thus their disruption of the readability of the painting was considerably reduced. This emphasized the original, surviving paint surface and allowed it to be more greatly valued. This

“level switch” is as effective on paintings with a precise and constant stratigraphy (e.g., most easel and mural paintings) as it is on a variety of other artifacts (e.g., painted wooden sculptures and ceramics). Within the *teoria del restauro*, this technique—which, strictly speaking, is not inpainting but a different method for the treatment of losses—is always deemed preferable, though carefully weighed against the aesthetic limitations it imposes.

For losses in which the reconstruction of the image is deemed necessary and possible without arbitrary interpretations, the *teoria del restauro* proposes the use of a technique of inpainting that is recognizable only through close examination: *tratteggio*. Thin vertical strokes of highly contrasting colors, traced in very close proximity to one another on the white base of the gesso fills, reconstitute the image with sufficient accuracy to guarantee the complete illusion of the absence of a lacuna.

The broader influence of the *teoria del restauro* has been limited by several factors. Primary among these is its limited dissemination outside the Romance-speaking world, as it was not translated before the 1990s. Although many European countries have shared Brandi's approach and methods, limitations arise, also in Italy, from considerations about the supposed need for a trained eye in the observer and about the higher costs of a longer process of loss compensation.

Despite the fact that the *teoria del restauro* proposes a structured formula for the reintegration of losses (Mora, Sbordoni-Mora, and Philippot [1977] 1984), it also leaves margins for the necessary subjectivity of the ultimate choice among the various possibilities that each problem presented by the painting allows. Although both the mimetic and the recognizable inpainting methods are viable, for each specific problem, the process that leads to a solution can only be guided by gradual comprehension, which requires lateral thinking and is based on trial and error.

More recently, by an interesting coincidence, the term *inpainting* has also been adopted in software language, in the reconstruction of missing parts in digital photographs and videos. Algorithms that extrapolate information from the surviving areas around these missing parts are used to reconstruct them according to the criterion of the minimum visual interference.

These semiautomated methods are structured according to the mechanisms of human visual perception described by Gestalt psychologists (among others) and are proposed for the treatment of missing parts in digital photographs of old paintings (Schönlieb 2015). Such techniques will soon become available for use in combination with digital printing methods, which have recently been successfully used for transferring printed images in the losses of wall paintings in order to assist and reduce manual inpainting. Prefabricated elements introduced in the integration work carried out by the conservator may add a new level of efficiency to the process and make the integration of large losses more cost-effective.

When heritage has been damaged by war or by natural disasters, complete reconstructions are often asked for in order to preserve its symbolic meaning in terms of collective identity. The decision process ought to be rooted in the clear understanding of the requirements of the stakeholders, which need to be harmonized with the physical condition and needs of the artifact. In a time of frequent war conflicts and rapid technological developments, conservators need to exert special awareness.

In conclusion, if inpainting has been the object of reflections and successful prescriptions, the part of it that is performed on the original paint has been, and still is, considered risky, even though it is now always performed with reversible paints. As a matter of fact, inpainting involves the risk of regressing to the practices of overpainting, from which the modern profession has moved away with determination.

Inpainting is defined alongside its process and intrinsically connected with its action. For this reason most of the responsibility stays with the “critical action” of the conservator, which in turn depends on his/her sensitivity while facing constantly changing challenges. The maturity of the profession, nowadays guaranteed by the availability of highly specialized conservators and by their close interaction with the other professions, allows relying on a higher level of awareness at an international level. Nevertheless, most of the theoretical frameworks of inpainting have been produced by professionals who do not have direct responsibility (Muñoz Viñas 2005) for the operations performed on the artifact.

The new technological frontiers and the aesthetic demands of a world dominated by perfect images in an “age of tourism” raise new challenges for conservation ethics. In a global society that seems to be progressively less willing to accept the presence of imperfections in artifacts with a shared value, a bigger effort to discuss and bridge between professionals and the other stakeholders seems to be more urgent by the day.

SEE ALSO: Archaeology and Tourism; Ethics in Conservation; Experts and Stakeholders

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Laser Cleaning

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Lasers have been introduced in the cultural heritage (CH) conservation science during the last 25 years and have progressively established themselves as unique tools for approaching complex diagnostic and restoration problems efficiently (Cooper 1998; Fotakis et al. 2006). The high intensity of a laser beam, its monochromaticity (the ability to be emitted in a single or in a narrow band of wavelengths), its directionality, and its coherence are unique properties that enable spatial confinement, selectivity, remote action, immediate control, and feedback and thus made possible the broad use of lasers for analytical and cleaning purposes in the CH field.

Laser–material interaction is a multiparametric process influenced by several parameters, including the physicochemical properties of the material and the operational characteristics of the laser system. The former refers to properties inherent of the material and thus particularly influential for its behavior upon laser irradiation, as for example the absorption coefficient (α), thermal conductivity (k), heat capacity (C) and molecular weight (MW). On the other hand, the laser characteristics—that is, its wavelength (λ), intensity, fluence (i.e., energy per unit area: $F = E/S$), pulse duration (τ_L), repetition rate, and beam quality—can be carefully chosen and thus the optimum laser–material interaction can be defined and selected (Georgiou, Anglos, and Fotakis 2008).

The fine-tuning of these parameters regulates and controls how much of the incident laser radiation will be absorbed, transmitted, and scattered by the irradiated material, and therefore affects specific applications (e.g., imaging, analysis, modification, and processing/removal of materials). Moreover, the relative percentage of the radiation absorbed by the substrate is decisive for

subsequent phenomena (thermal/photochemical modifications, plasma formation) or for the reemission of fluorescence and phosphorescence, and hence favors analytical, diagnostic, or material processing applications.

Along these lines, a laser beam focused on a material can reveal valuable information on its chemical composition on the basis of spectroscopic analysis (Nevin, Spoto, and Anglos 2012), while, conversely, when the laser beam is shined onto a wider area of the object, laser interferometry enables the detection of hidden alterations and structural defects (Tornari, Tsiranidou, and Bernikola 2012). In case of favorable conditions, lasers may, on the principle of laser ablation, induce progressive and controlled removal of layers. Laser ablation relies on the synergy of thermal, photochemical, and photomechanical effects and is a quite complex process. Upon optimization—that is, for a laser beam of intense energy density and short pulse duration, which is emitted at a wavelength that is strongly absorbed by the material—laser ablation may result in controllable material removal, with negligible thermal load or damage to the remaining material. As a result, in a variety of CH conservation challenges, altered overlayers and unwanted accumulations can be selectively removed, to reveal the original surface.

The most crucial issue for a successful cleaning intervention is the revealing of the original surface without any damage, and therefore spatial confinement and control of the laser ablation effects is important. “Self-limiting” mechanisms in laser ablation are responsible for many successful cleaning interventions, but this condition does not apply to all cleaning challenges; thus extensive studies have been carried out with the aim of proving and establishing laser cleaning.

Although the use of lasers to eliminate material in industrial (processing and microelectronics) and medical (eye/dental surgery) applications is well established and extensively studied both at the theoretical level and in practice, further studies are necessary for a smooth transition to the CH field. These studies refer to the systematic

investigation and elucidation of the associated ablation mechanisms, the assessment of potential chemical and thermal modifications induced in the remaining material (Georgiou, Anglos, and Fotakis 2008), and the understanding of side effects (Pouli et al. 2012). During the past 25 years operative laser parameters were confidently optimized and cleaning methodologies for each conservation challenge were developed and fine-tuned. Thus nowadays, having acquired this experience as well as some critical evaluation by comparison to conventional cleaning practices, laser cleaning is established and conservators and restorers have the choice of using highly sophisticated laser-cleaning systems. Furthermore, technological improvements allowed the transfer of laser technology on site and several successful laser-cleaning applications *in situ* have been reported, for example the removal of black pollution accumulations from St. Stephen's Cathedral, the Amiens Cathedral, and the sculptures of the Athenian Acropolis (Pouli et al. 2016), the cleaning of the gilded decorations on Florence monuments (Siano and Salimbeni 2001), and the removal of acrylic overpaints from the "black" oil paintings by Ad Reinhardt (Melessanaki et al. 2006).

A key parameter in laser cleaning is the absorptivity (at the operative laser wavelength) of the involved materials. Absorptivity determines the ablation threshold (the critical fluence value designating initiation of the material removal process) and the thickness of the removed material. Furthermore, it influences the extent of any thermal and chemical effects that may be induced in the remaining material. In fact, a highly absorbed laser beam will result in effective material removal (in thin layers and low ablation thresholds), with minimal alterations to the remaining surface. Obviously, the optimum operative laser fluences must lie above the ablation threshold in order to avoid undesirable side effects on the treated surface or in the surrounding areas (swelling of organic materials, selective vaporization of particulates in case of complex crust structures, etc.).

Removal of dark encrustations (pollution accumulations, corrosion layers, excavation crusts) from various substrates (stonework, metal) usually involves infrared (IR) laser systems and relies on photothermal mechanisms. In most cases there is a significant difference in the

absorptivity of the involved materials; this effectively leads to a considerable difference between the encrustation threshold fluence and the one that could potentially damage the substrate, and hence the cleaning process is "self-limiting" (Cooper 1998). Similarly, IR and visible (VIS) laser cleaning methodologies have been proposed for the removal of contaminants and particulates from paper and parchment, as photochemical modifications to the substrates (the cellulose content of paper, or the collagen of parchment) are circumvented in these cleaning regimes.

The photothermal cleaning regime has also been associated with unwanted side effects, for example discoloration. Indeed the yellowing reported upon IR laser irradiation on marble surfaces with pollution encrustation and on natural cellulose materials with carbonaceous contamination has seriously compromised lasers as cleaning tools. Several hypotheses have been introduced to explain such discoloration; the presence and nature of soiling particles have a key role in this undesired side effect. Given that no discoloration was observed upon the irradiation of unsoiled papers or parchments, the yellowing is related to laser-induced thermal degradation of cellulose or collagen, which is due to the presence of the soiling particles that may enhance or favor excessive heating phenomena. In stonework conservation, yellowing is a very complex issue for many reasons—it can be due to the complexity of the materials involved (including in past conservation treatments), to the popularity of laser cleaning in the field, and to the high number of cleaning projects—and therefore many studies were devoted to its explanation.

Along these lines, the synchronous use of IR (1064 nm) and ultraviolet (UV, 355 nm) laser pulses was shown to be able to overcome discoloration effects upon the removal of pollution crusts from marble (Pouli et al. 2012) and was thus successfully applied on the Parthenon sculptures in Athens. The success of this cleaning scheme is based on the combined action of two discrete ablation mechanisms, exemplified by the use of laser pulses of two wavelengths, in spatial and temporal overlapping and in various fluence ratios (F_{IR}/F_{UV}). Both the careful choice of the ratio of applied energies and the individual fluences of each wavelength are decisive for optimum results.

Discoloration (darkening) is also encountered upon direct laser irradiation of painted surfaces. The sensitivity of many pigments to light and temperature is particularly relevant when considering intense laser irradiation, which upon interaction can lead to the localized and rapid heating of the pigment. Significant research has been devoted to the understanding of these undesired side effects and to the definition of the boundary conditions in which laser cleaning can be safely applied on painted surfaces (Pouli et al. 2012). It has been shown that in most cases the darkening of pigment particles is independent of the wavelength of the applied radiation or of the binding media but can be significantly controlled for ultrashort irradiation regimes. It should be also noted that, although the perceived color change is often intense, pigment discoloration usually refers to the outermost particles of the paint, and thus the straightforward identification of the associated physicochemical modifications is extremely surface-specific and particularly difficult.

Along these lines, in paintings conservation UV lasers are employed to eliminate the outermost surface of the aged or degraded natural or synthetic varnish coatings (Pouli et al. 2010). For example, the laser-assisted removal of the outermost cross-linked hard varnish layers using a KrF Excimer laser beam (248 nm), which is strongly absorbed by the majority of aged varnishes, is well studied, while it is confirmed that the mechanisms governing this layer-by-layer cleaning scheme are mainly of a photochemical nature (bond breaking and dissociation) and any thermal effects (heat generation and diffusion) are negligible. In parallel, to support this approach and to investigate quantitatively the extent of chemical modifications that may be induced in the remaining material after ablation, a series of studies using technical samples composed of polymeric films doped with low concentrations of well-defined photosensitive molecules were undertaken. The laser-induced fluorescence of the photoproducts on the irradiated surfaces was monitored in a pump-probe scheme, with the aim of studying the evolution of chemical modifications and their dependence on parameters such as the applied laser fluences, the number of pulses, and the material properties (Georgiou, Anglos, and Fotakis 2008). Technical samples of higher complexity (series of layers simulating the

different strata of real easel paintings and icons) were also investigated, while other cleaning regimes (e.g., ultrashort pulses) or wavelengths were also examined with encouraging results.

Ultrashort (picosecond (ps, 10^{-12} s) and femtosecond (fs, 10^{-15} s)) lasers have been introduced in conservation research because they offer particular capabilities for material processing and overcome several of the nanosecond (ns, 10^{-9} s) laser ablation limitations (Pouli et al. 2010); they may process even nominally transparent substrates (owing to multiphoton processes), while thermal degradation phenomena are significantly eliminated. As a result, the morphological aspects of the fs-processed substrates are far superior to those attained with ns laser pulses, and thus ultrashort laser material ablation is considered to offer greater control and confinement.

Other laser cleaning methodologies involve the use of far-IR wavelengths (2940 nm) emitted from an Er:YAG laser (Andreotti et al. 2007). This cleaning scheme, initially introduced for the removal of varnishes and overpaintings from easel paintings, relies on the selective excitation of molecules that contain hydroxyl (OH) groups and is clearly differentiated from mechanisms of lasers operating in the UV, VIS, and near-IR range. Gradual and selective cleaning of very thin layers is achieved if and only if organic solvents are employed on the surface before and during the laser irradiation.

Laser cleaning is an established and most valuable cleaning methodology, with numerous successful applications in the conservation of CH objects and monuments. Its superiority to alternative cleaning techniques (e.g., solvent and mechanical cleaning) lies in its ability to ensure effective cleaning and minimal chemical alterations to the underlying and adjacent material.

Nevertheless, given the irreversible nature of this process, lasers, like all cleaning tools, should be cautiously employed, to prevent unpredicted mistakes and irreparable damage, and should not be considered as a panacea or a trivial procedure. In this respect it is advisable, prior to any laser-cleaning intervention, to carefully define the conservation problem, determine the physicochemical properties of the materials involved, and set and optimize the working parameters of laser cleaning through preliminary studies and

thorough an assessment of related laser tests. In situ and online monitoring of the laser ablation process is also advisable, in order to ensure a safe and controlled cleaning, with high spatial confinement (ideally, restricted to the beam size) and depth resolution (of submicron level).

SEE ALSO: Conservation Science;
Laser-Induced Breakdown Spectroscopy (LIBS)

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Microchemical Tests in Conservation

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Chemical characterization or spot testing is particularly important for the qualitative identification of archaeological and historic materials undergoing examination and treatment. Some forms of physical information may not survive these activities, so it is useful to identify and record as much material information as possible prior to any changes due to cleaning or consolidation. Archaeological conservators are frequently confronted with decisions regarding possible stabilization treatments that are dependent on characterizing the compositional materials of an artifact. In an excavation situation, there may not be time, funding, or access to instrumental techniques for material identification beyond the use of the human eye. Less expensive microchemical spot tests, however, often provide the needed information because they do not require elaborate instruments or specialist participation. While standardized instructions and techniques for reagent preparations and application are sometimes considered old fashioned and are no longer taught, spot tests remain a practical, sensitive, and useful tool in archaeology.

The characterization of distinctive qualities or characteristics of various materials begins with questions concerning the specific nature of an artifact material, its technology, and aspects of its condition (such as deterioration). Specific artifact materials to be considered might include metals, ceramics, plasters, glasses, stone, pigments, bone, wood, fibers, gums, resins, and miscellaneous accretions. Tests for metals may identify hardness, color, or alloying. Tests for ceramics may correlate aspects of contaminant salts, temper, inclusions, or porosity to condition. Chemical tests are useful for distinguishing marble, plasters, shell, and calcareous accretions. Inorganic coatings may be identified by tests that

differentiate carbonates, sulfates, and chlorides. Tests for organic coatings, deposits, or adhesives may distinguish proteins, starches, gums, and resins. Specific tests for the materials that are contextual to the artifact might include analysis of the soil or ground water and dissolved solids. Various tests for soluble and semisoluble salts and pH are useful in a number of contexts. The material characterization of the supplies used in conservation treatments is also important and may include tests for water purity, adhesives, coatings, and storage materials (plastics, papers, labeling materials).

Beginning in the twentieth century, various tests were developed for microchemical analysis, but few were recorded to characterize the composition of materials found in archaeological contexts. The major developments and subsequent revisions of systematic chemical spot-test analysis by Fritz Feigl (1937) and Arthur Vogel (1937) remain important references for isolating organic and inorganic materials. Typically, these spot-test reactions have been successfully applied in clinical analysis, air quality testing, food and water analysis, geochemical prospecting, and forensic laboratories. However, within the literature of these disciplines, the style of test format varies considerably, thereby making it difficult to compare testing of the same materials by different tests. Moreover, most of these test descriptions are limited to chemical procedures that were designed for use by chemists who would not necessarily need reminders of such aspects as reagent preparation, storage, and safety, or the chemical principles involved. The role of the archaeological conservator is to prepare and interpret test results, as well as identify the potential damages that can occur to artifact samples as a consequence of doing the tests.

Despite the rapid application of modern instrumental analytical techniques such as chromatography, mass spectroscopy, and electroanalytical analysis, the search for simpler, safer, and less expensive tests has continued to be important for many applications in archaeology. In recent decades, much of the research in spot

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tests included reviews of older tests. The early work of Friedlieb Runge in 1842 as reported by Anft (1953) involved the use of impregnated papers to accommodate a scientifically checked spot reaction and he is credited with producing the first spot-test papers. In the discipline of conservation, Rutherford Gettens and George Stout developed and refined numerous tests for the analysis of artist materials. Unfortunately, most of their research on microchemical analytical techniques remains in the form of an unpublished notebook located in the Fogg Museum at Harvard University.

Following developments in analytical instrumentation, a reliance on chemical characterization techniques has declined. However, because of the demand for easy, safe, and economical testing techniques, commercial chemical companies have been encouraged to produce simple and compact spot-testing systems. Many new special spot-testing papers have applications in answering questions posed with historic and artistic artifacts. In pottery there are questions that relate to the pigments used for designs, the composition of temper, the nature of inclusions, the composition of efflorescing salts, or the types of residues associated with the object. Aspects of groundwater contamination or the possible presence of fertilizers if the excavation site has also been used for agriculture can be tested. In organic materials it is possible to chemically distinguish if a plant material is a leaf fiber or stem fiber, or if a residue is animal or plant based.

While once the fundamental technique of analytical chemists, spot testing can be useful to nonchemists seeking a safe and easy way to perform analysis. An understanding of exactly what is being tested for is the first stage. For example, a test to identify black pigments on pottery (Nelson 1975) actually identifies the iron component of black pigments in order to distinguish them from carbon-based pigments that are also found on pottery. Knowing that the identification of iron is the key concept in this example makes it apparent that there are broader applications for this particular test beyond pottery color determination. Most tests work best if the question is based on the presence of a material rather than a broadly based "What is it?" type of question.

Although the theory of materials characterization has been discussed in recent years

among excavation conservators, a systematic methodology for microchemical testing was not published until 2000 (Odegaard, Carroll, and Zimmt) and a subsequent edition (2005) directs their application towards conservators, archaeologists, and museum specialists. Prior to these compendiums, there was a general mistrust of chemical tests and a reluctance to use them in archaeology because they were often based on inaccurate, incomplete, and poorly written class notes and hand-outs with multigenerational photocopies from unreferenced publications. For example, many of the earlier chemical spot-testing instructions failed to identify or explain interference materials, or to elaborate on the various chemical processes and stages of a reaction. Additionally, it was common to report the color designation of a positive reaction but neglect to indicate how long a reaction could take or what a negative reaction might appear as.

Important modifications to the recommended reagents and their application techniques make these tests less damaging to objects or samples. Archaeological conservators have found ways to change the way chemical spot testing is done and they understand why it is difficult to use standard chemical testing references that are designed for other situations. There is finesse to finding a suitable and unobtrusive place for the testing on artifacts. Unfortunately, even the most delicate of tests can scar an object, so if the test can take place on a different surface, the chemical reagents will not damage the object itself.

The idea of transferring part of the object's material to another substrate and doing the test on that substrate is the key to saving an object from further damage. For example, the use of filter paper dampened with de-ionized water can facilitate the capture of tiny pigment particles fallen from an object or found in a storage container. Thus, the tiniest particle can be tested with no further loss of pigment from the artifact. Another technique involves using tiny pinhead-sized pieces of filter paper pulled from the edge of a larger sheet. Rather than placing chemical drops directly on the artifact, the reagent can be added to the small paper which can then be placed strategically on the artifact. This technique is particularly useful on artifacts as they tend to have more irregular surfaces than normal laboratory test blanks. Also, reagents

that have low surface tension may flow readily over the surface of the object and spread from an inconspicuous test area to other areas, possibly causing damage to the artifact. By using the tiny filter paper modifications there is greater control of the reagent.

The critical component for comparing the reactions is the use of a known positive sample and a known negative sample with the unknown artifact sample. These are important for developing confidence with a test. Having known samples that can be tested with repeatability is a critical part of a microchemical test. If a reaction is the same for the known positive, the known negative, and the unknown, there is a problem. It might be the analyst, the reagent, the technique, or contamination. The problem of contamination would be impossible to detect if only the unknown was tested. By using the knowns, a positive result on all samples would indicate that the test was inconclusive and the test process would have to start over.

Spot-test plates are available in ceramic (light and dark) or clear glass with varying numbers of testing wells. A white one is useful if the anticipated reaction is colored or dark, and a dark plate is necessary when there will be a white precipitate or a light-colored reaction. Sometimes there is a subtlety in the color of the reaction solution and a clear plate is useful because a light source can be manipulated against a variety of backing materials. For some tests the etched end of a microscope slide is useful. Capillary tubes and Pasteur pipettes can be used to create a sample chamber that isolates the smallest of sample materials. When placed in the funnel part of the pipette, the tiny particle of sample can be tested with spot-testing papers, while the chamber facilitates viewing of the test paper reaction, particularly if pyrolysis is involved as there is time to examine changes in sample color or form, or to detect an odor afterwards. Safety in spot testing involves the use of personal protective equipment and proper reagent disposal for the small amounts of solvents and chemicals that are used.

The reporting of microchemical test results is the critical and final part of the process. Documentation allows for review and comparison of a test procedure and the results over a wide span

of time. When a reaction is unusual, it is possible to go back to the notebook or file and check if that reaction has occurred before. A reliance on sophisticated instrumental techniques of analysis requiring outside specialists to answer many fundamental questions is very useful when it is available, but there are many questions that can be answered with well-defined spot tests.

SEE ALSO: Conservation Science

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Mineral Inorganic Treatments

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Consolidation is one of the most important steps in the conservation process of deteriorated objects as it re-establishes cohesion between disintegrated particles of powdery surfaces. Extensive studies carried out over the course of past decades have indicated that choosing a proper consolidant to regenerate cohesion of loose or friable surfaces of porous materials such as stone artifacts, wall paintings, or archeological bones is critical and at the same time extremely challenging. This is specifically related to being able to ensure sufficient penetration beneath the surface layer, while also providing mechanical strength and abrasion resistance. Consolidation is normally carried out through the application of liquid solutions, which are placed in contact with the damaged surface and allowed to interact with the material through various physical and chemical processes. The end product, which is formed as a result of these reactions, helps to mitigate the capacity for movement between very small particles of originally weakened surface, thereby altering the characteristics of the material in terms of its physical–chemical behavior, particularly in the presence of water (permeability). It tends to make the material stronger in compression and tension but may also affect inherent characteristics, such as heat and sound transmission, rigidity, or optical properties. An optimal consolidant has to be environmentally friendly, suitable for object or site application, should not severely alter the original “nature of the porosity” (clog pores), and cannot be extremely hydrophobic as this could lead to further damage. Ideally, the consolidant should also be photochemically stable to prevent optical changes of the surface that could affect significantly the saturation of color, gloss, and texture. Other key factors considered in the consolidation include

compatibility of the thermal expansion coefficient with treated material, and retreatability, which is enabling future treatments (if necessary), or good resistance towards biodegradation and physical or chemical environmental effects (wind or sand abrasion, chemical attack such as chloride or sulfate ingress or acid rain).

Starting from around the middle of the twentieth century, organic polymers, mainly acrylic, vinyl, and silicone based, have been widely used as consolidants for heritage objects. However, in many cases, polymers used for the consolidation exhibited poor penetration, and being chemically incompatible with the original surface often induced further degradation of the artwork by changing greatly the physical–chemical properties due to hydrophobicity, embrittlement, yellowing over time, shrinkage resulting in delamination, blocked pores, and so on. As such, various alternative methods to organic polymers which are based on the application of inorganic mineral treatments have been proposed (Hansen et al. 2003; Matteini 2008). These approaches have proven to be often more suitable given the original nature of many artifacts such as wall paintings and calcareous stone objects.

Historically, limestone-based antiquities and wall paintings, particularly those of fresco application, have been treated with a saturated calcium hydroxide solution (“limewater”), which eventually resulted in a calcium carbonate formation. The consolidation mechanism of this method is based on the transformation of $\text{Ca}(\text{OH})_2$ into calcium carbonate (CaCO_3) through a carbonation process induced by the CO_2 in the atmosphere following chemical reaction, as shown in Table 1. However, because of the limited solubility of calcium hydroxide (1.73 g/L at 20 °C), limewater has to be applied in successive applications to ensure sufficient deposition of the consolidant. Multiple treatments, however, may block pores and alter the natural “breathing” of the surface while reducing penetration of the consolidant. Furthermore, low stability of the system and high surface tension of water (as the medium) can also cause aggregation and phase separation. All these may

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lead to insufficient consolidation and aesthetically undesired “whitening” of the surface.

Further risk associated with this method is linked to the introduction of large amounts of water, which may mobilize soluble salts (if any are present in the system) and induce additional stresses through dissolution and recrystallization or freezing and drying processes (Hansen et al. 2003). As solubility of $\text{Ca}(\text{OH})_2$ is inversely proportional to the temperature, to maximize concentration in the solution, colder temperatures have been suggested. However, maintaining such conditions can be a challenging task from a practical perspective. As such, in search for improvements, several strategies including “sucrose methods” to increase $\text{Ca}(\text{OH})_2$ solubility and the synthesis of $\text{Ca}(\text{OH})_2$ nanoparticle–alcohol dispersions (Ambrosi et al. 2001; Rodriguez-Navarro, Suzuki, and Ruiz-Agudo 2013) to prevent agglomeration and boost penetration have been explored. It has been demonstrated that the synthesis of $\text{Ca}(\text{OH})_2$ particles exhibiting size lower than 300 nm and their proper dispersion in suitable solvents allowed for the improved penetration through the surface layer of the object. Solvents such as ethanol or propanol yielded slower sedimentation and agglomeration rates in comparison with aqueous media and reduced the risk for the formation of a white veil on the surface. Examples of such a successful consolidation were shown by Ambrosi et al. (2001). $\text{Ca}(\text{OH})_2$ has also demonstrated good compatibility when used as a de-acidifying agent in the conservation of paper and water-logged wood where formed CaCO_3 acted as an effective alkaline reservoir. Nanostructured $\text{Ca}(\text{OH})_2$ was also tried as a consolidant for demineralized archaeological bones and it was noted to increase their strength when compared to the untreated samples. Yet, in spite of improved working and resulting satisfactory outcomes, there are several drawbacks associated with this consolidation method. First, the pH of $\text{Ca}(\text{OH})_2$ solution is quite high (~ 12.5) so it can affect some of the pigments used to make the artifact, which are sensitive to alkaline conditions. Second, while color changes are less of a concern in case of stone consolidation, dissolution of CaCO_3 upon a drop in the pH caused by acid rain and other acid local environments, especially when the object or monument is placed outdoors, could be a problem.

Potential phase transformation into gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) in the presence of sulfate ions (known as “sulfation”) poses another limitation on the use of $\text{Ca}(\text{OH})_2$ -based consolidants. When large amounts of soluble sulfates (e.g., sodium or magnesium sulfates) are present, for example in a wall painting, sulfate ions may react with calcium hydroxide, producing slightly soluble gypsum. The final result is the lack of consolidation effect and an unwanted formation of white crusts resulting from the newly formed gypsum salt.

For many years, the barium hydroxide method (Hansen et al. 2003; Baglioni and Giorgi 2006; Matteini 2008) has been considered an alternative and improved consolidation treatment to the calcium hydroxide method, as atmospheric carbonation enables formation of a barium carbonate consolidating layer of relatively low solubility. To address the problem of sulfation, the barium hydroxide ($\text{Ba}(\text{OH})_2$)-based treatment, also known as the Ferroni–Dini method or the “Florentine method,” was developed following the disastrous flood of Florence in 1966. This treatment employs a two-step process to block sulfates present in mobile form and to consolidate through the atmospheric carbonation process (Table 1). An example of the restoration performed on a wall painting using this method was demonstrated by Baglioni et al. (2008). First, gypsum is transformed with a solution of ammonium carbonate that converts it into calcium carbonate and soluble ammonium sulfate. In subsequent treatment with barium hydroxide, the ammonium sulfate is converted into barium sulfate which is an inert and insoluble salt. In this way sulfation is arrested. Owing to the new formation of barium carbonate and barium sulfate, the porosity is reduced and the system is expected to be less susceptible to the environmental pollutants, soluble salts intrusion, or even potentially acid rain dissolution. However, proper application procedures must be followed to prevent whitening or “bloom.” For all these reasons, barium compounds have been considered desired consolidants due to their compatibility with a substrate, minimal effect on the appearance, preservation of the original hydrophilic properties of the surface, and effectiveness in transforming gypsum into an insoluble salt. It has been noted, however, that there are also several drawbacks associated with barium treatments:

Table 1 Basic chemical reactions associated with inorganic consolidation treatments.

<i>Inorganic consolidant</i>	<i>Basic chemical reaction(s)</i>	<i>Action</i>	<i>Remarks</i>
Ca(OH) ₂ Ba(OH) ₂	$\begin{aligned} &\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \\ &\text{CaSO}_4 \cdot 2\text{H}_2\text{O} + (\text{NH}_4)_2\text{CO}_3 \\ &\quad \rightarrow (\text{NH}_4)_2\text{SO}_4 + \text{CaCO}_3 + 2\text{H}_2\text{O} \\ &(\text{NH}_4)_2\text{SO}_4 + \text{Ba(OH)}_2 \rightarrow \text{BaSO}_4 + 2\text{NH}_3 + 2\text{H}_2\text{O} \end{aligned}$	Consolidation Desulfation Desulfation Consolidation Consolidation Consolidation	
(NH ₄) ₂ C ₂ O ₄	$\begin{aligned} &\text{Ba(OH)}_2 + \text{CO}_2 \rightarrow \text{BaCO}_3 + \text{H}_2\text{O} \\ &\text{Ba(OH)}_2 + \text{CaCO}_3 \rightarrow \text{BaCO}_3 + \text{Ca(OH)}_2 \\ &\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O} \\ &\text{CaCO}_3 + (\text{NH}_4)_2\text{C}_2\text{O}_4 \rightarrow \text{CaC}_2\text{O}_4 + \text{H}_2\text{O} + 2\text{NH}_3 + \text{CO}_2 \\ &\text{CaSO}_4 \cdot 2\text{H}_2\text{O} + (\text{NH}_4)_2\text{C}_2\text{O}_4 \\ &\quad \rightarrow \text{CaC}_2\text{O}_4 + (\text{NH}_4)_2\text{SO}_4 + 2\text{H}_2\text{O} \end{aligned}$	Consolidation Desulfation	Calcium oxalate may precipitate in a form of mono- or dihydrate.
(NH ₄) ₂ HPO ₄ (NH ₄) ₃ PO ₄	$\begin{aligned} &10\text{CaCO}_3 + 6(\text{NH}_4)_3\text{PO}_4 \rightarrow \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 \\ &\quad + 18\text{NH}_3 + 10\text{CO}_2 + 8\text{H}_2\text{O} \\ &10\text{CaCO}_3 + 6(\text{NH}_4)_2\text{HPO}_4 \rightarrow \text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2 \\ &\quad + 18\text{NH}_3 + 10\text{CO}_2 + 8\text{H}_2\text{O} \end{aligned}$	Consolidation Consolidation Desulfation	In a real-world scenario, HAP is anticipated to precipitate as nonstoichiometric salt where PO ₄ ³⁻ and/or OH ⁻ groups are replaced by CO ₃ ²⁻ . It can also be calcium deficient where Ca ²⁺ ions are partially substituted by NH ₄ ⁺ . Matteini et al. (2011) also proposed (NH ₃)H ₂ PO ₄ as consolidating agent, but to offset lower pH associated with this consolidant their system was equilibrated with addition of NH ₃ .

(1) They are not appropriate for substrates rich in magnesium carbonates (plasters made with dolomitic lime or dolomitic marble statues) due to the formation of highly soluble magnesium sulfate (Hansen et al. 2003); (2) when nitrates are present (due to the precipitation of insoluble barium nitrate); and (3) they can cause chemical changes to the copper-based pigments. Additionally, the high alkalinity of barium hydroxide can severely damage organic binding media such as egg tempera if any are present in secco mural paintings. There are also questions and concerns related to the toxicity of barium, and not all nations permit the use of barium in conservation.

In the early 1990s, calcium oxalate-based treatment was proposed (Hansen et al. 2003; Matteini 2008). This method, inspired by the observation of naturally formed oxalate patinas, was developed mostly for the historic objects and monuments subjected to the outdoor environment where acid rain and following dissolution of carbonate material are points of concern. As such, the formation of a protective oxalate layer due to its reported low solubility and high stability in a wide pH range (Matteini 2008) is expected to mitigate this dissolution and act as an ideal passivation agent for calcium carbonate objects subjected to urban acidic atmosphere. Oxalate treatment employs highly soluble ammonium oxalate solution through the application of a cellulose poultice compress subsequently placed on the calcium carbonate-based surface. As a result of this interaction (Table 1), protective film consisting of fine calcium oxalate crystals is produced. Oxalate treatment can also act as an effective desulfating agent (Table 1) as it reacts with gypsum in a similar way as it reacts with calcium carbonate. The ammonium sulfate that remains can be subsequently removed through a desalination process using compresses of deionized water and cellulose pulp. The transformation of gypsum into calcium oxalate is advantageous as it prevents further mobilization, transport, and crystallization of gypsum, which could damage the wall painting or sculpture. Additionally, due to calcium oxalate formation at the surface and subsurface, mitigated penetration of salts into a porous matrix has been recorded. There is, however, a certain challenge associated with this treatment as limited penetration and consolidating effect have been noted. Most notably, yellowing discolorations

in oxalate-treated stones or mortars may occur, mainly those containing free iron (III) in their structure. The ammonia present in the precursors may also damage certain copper-based pigments such as malachite and verdigris.

Recent studies have demonstrated a considerable potential for developing much improved inorganic consolidation treatments by biomimicking the growth of hydroxyapatite ($\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2$, HAP) on calcium-rich matrices (Sassoni, Naidu, and Scherer 2011; Balonis and Kakoulli 2013; North, Balonis, and Kakoulli 2015). Hydroxyapatite is the main mineralogical component of teeth and bones responsible for their strength and rigidity. As such, when induced as a consolidant it results in improved mechanical properties of the surface/subsurface, as well as reduced water sorptivity without clogging pores or causing whitening on the surface. It has very low solubility and exhibits good stability in pH ranges from approximately 4 to 14, which like the oxalate treatment makes it suitable for outdoor applications. Formation of a protective HAP crystals network is induced by triggering reactions between the calcium in the calcium carbonate-rich matrix and highly water-soluble ammonium phosphate precursor (Table 1). This aqueous solution can be introduced through spraying techniques or cellulose poultice; the latter seems to provide a better control of application technique and homogeneity in the distribution of the final product. Calcium ions are not anticipated to reprecipitate as calcium carbonate due to the fact that the solubility product of HAP ($\log K_{\text{sp}} = 1.6 \cdot 10^{-117}$) is much lower than that of calcite ($\log K_{\text{sp}} = 3.4 \times 10^{-9}$). This treatment has also demonstrated better penetration into porous materials when compared to the oxalate-based consolidation (Sassoni et al. 2011; Balonis and Kakoulli 2013). In addition to consolidation, ammonium phosphate salts are anticipated to serve as desulfurization agents, converting damaging gypsum into HAP (Table 1). However, at lower pH conditions or when not enough calcium is available to form hydroxyapatite, other calcium phosphate salts such as brushite ($\text{CaHPO}_4 \cdot 2\text{H}_2\text{O}$) may also form. The method is especially encouraging when it comes to the consolidation of wall paintings, containing pigments and binding media (e.g., egg tempera)

that exhibit sensitivity to a high pH. The selection of a proper precursor such as diammonium phosphate $((\text{NH}_4)_2\text{HPO}_4)$ solution at pH of approximately 8 allows for the prevention of aggressive alkaline conditions. Apart from wall paintings and outdoor monuments, hydroxyapatite consolidation has also shown promising results for archaeological bone conservation (North et al. 2015) as due to its nature it is more compatible with original material and may serve as a great alternative to polymeric consolidants, which are commonly used for bone, teeth, fossil, or ivory preservation. However, several things need to be kept in mind when using this method. First of all it involves ammonia which can cause damage to copper-based pigments. Additionally, to avoid aesthetically undesirable whitening of the surface, pigment degradation, or blocking pores which can be detrimental, treatment should be designed with regard to appropriate ammonium precursor type, concentration, and time of contact (Balonis et al. 2013).

In conclusion, when considering consolidation, “not one size fits all,” as reaction chemistry (type of consolidant, concentration, pH, additives), as well as application method (poulticing, spraying, immersion) and time have to be tailored to the specific objects, bearing in mind their chemical nature (including binding media present if any, impurities, pigments) and exposure conditions (outdoor, indoor, temperature, pollutants, acid rain, etc.). In addition, from a practical perspective, toxicity of treatment and feasibility of application technique need to be considered.

SEE ALSO: Ancient Mortars and Plasters; Characterization of Pigments; Chemistry in Archaeology; Conservation; Conservation in Museums; Conservation of Bone, Horn, and Ivory; Conservation of Earthen Building Materials; Conservation of Stone and Petroglyphs; Conservation Science; Deterioration; Deterioration of Earthen Building Materials; Deterioration of Stone and Petroglyphs

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Nanotechnology and Nanoscience in Conservation

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The importance of preserving material heritage has been acknowledged worldwide, as cultural and historical patrimony are sources of different benefits that comprise social inclusion, the transfer of aesthetic and ethical values to future generations, and economic improvement thanks to tourism and to the valorization of well-conserved artifacts. Science offers several possible solutions to the preservation of works of art, and research work in this field has mainly followed two distinct lines, namely the development of enhanced diagnostic techniques for the analysis of the artifacts, and the synthesis and formulation of materials to counteract the degradation of the works.

Significant effort has been dedicated to the development of advanced diagnostic methods with key features such as noninvasiveness of the analysis, enhanced detection limits (high sensitivity and specificity), feasibility (e.g., user-friendly software for end-users), and the use of portable instruments. Techniques such as laser-induced breakdown spectroscopy (LIBS), surface-enhanced Raman scattering (SERS), synchrotron-radiation-based X-ray techniques (Bertrand et al. 2016), nonlinear imaging spectroscopy (e.g., second and third harmonic generation (SHG and THG), multiphoton excitation fluorescence (MPEF), and fluorescence-based techniques), reflectance hyperspectral imaging, fiberoptic reflectance spectroscopy (FORS) (Cucci, Bigazzi, and Picollo 2013), diagnostic immunology (Cartechini et al. 2010), and multianalytical approaches (for instance combining thermal analysis with infrared spectroscopy, gas chromatography, and mass spectrometry) are

all examples of diagnostic tools that have been developed in the last decades according to one or more of the aforementioned criteria.

As a complementary research line to diagnostics, the development of advanced conservation materials saw significant improvement in the last decades in the framework of material, colloids, and nanosciences. This approach has developed since the 1980s, when urgent solutions were needed to remedy the damage suffered by precious artifacts in the aftermath of the 1966 Florence and Venice floods. Accordingly, the first methodologies were developed to tackle the conservation of fresco paintings and stone, in particular focusing on the removal of salts and other detrimental layers from the original surface of the artifacts, and on the mechanical strengthening of powdering and delaminated layers. Starting with these examples, several materials and methodologies have been developed in the framework of soft matter and colloids to achieve the cleaning, consolidation, and pH adjustment of degraded works of art, where fundamental requirements are the compatibility of the new materials with the original artifacts (whose physico-chemical properties must be altered as little as possible) and the minimal (or no) impact of the new materials on both the environment and the operators (conservators, curators, etc.). Two books have been published that illustrate the most important advancements in this topic (Baglioni and Chelazzi 2013; Baglioni, Chelazzi and Giorgi 2015a).

The cleaning of artifacts, intended as the removal of any detrimental or unwanted layer, is typically carried out as a preliminary intervention before other applications (e.g., consolidation) are performed. Advanced systems for this task have been derived from colloids science and soft matter, and comprise microemulsions and gels. The main advantage of these systems is that they grant improved performances as opposed to traditional cleaning materials such as solvent blends and thickeners. Microemulsions were applied for the first time on Renaissance wall paintings in the late 1980s, for the removal of wax spots (coming from votive candles) that were

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jeopardizing the painted surface (Baglioni and Chelazzi 2013). The rationale of this method is as follows: Low amounts of solvents (typically less than 10% w/w) can be dispersed as microemulsions (using surfactants) in a continuous water phase ("oil-in-water" systems, o/w). Knowing the phase-diagram of the composite system, it is possible to formulate cleaning fluids that are thermodynamically stable, optically clear, and isotropic, where the size of the microemulsions' droplets is in the order of nanometers. Such a small size grants a dramatic increase of the active surface area of the solvent droplets. These fluids can be applied either with a swab or loaded in poultices and gels. Surface dirt and soil tends to swell or dissolve in the fluids, becoming embedded within the micelles. The latter migrate into the poultice/gel, favoring the removal of the unwanted layer from the surface of the artifact. This is a key feature as opposed to the use of free solvents, where dissolved dirt or compounds tend to migrate within the porous matrix of artifacts (e.g., wall paintings, stone) and are not removed from the object. The microemulsion's droplets are also able to exchange solvents and surfactants with the soil or aged adhesives, which are consequently swollen and softened. The swollen layers can be removed with a gentle mechanical action, which grants a gradual and controlled removal. Another key advantage is that good cleaning effectiveness can be achieved while lowering the total amount of solvent needed in the cleaning system, as mentioned above, which addresses the well-known toxicity issue of most solvents used in the restoration practice. Finally, because they work through a different removal mechanism than that of free solvents, both micellar solutions and microemulsions have proven effective in some cases where the mere use of solvents did not allow the removal of complex layers of aged and detrimental adhesives or consolidants from past restorations (Baglioni et al. 2015a). Current improvements involve the presence of degradable surfactants (either biodegradable or cleavable) in the cleaning fluids, in order to avoid any rinsing step to eliminate nonvolatile residues from the treated surfaces. Microemulsions have been used in many real conservation case studies, and an example of the cleaning obtained with these systems is shown in Figure 1.



Figure 1 (Top panel) Wall paintings in the Conon Apse (Annunciation Church in Nazareth, Israel). On the left, the effect of aged polymer coating on the pictorial surface. On the right, the same area after complete removal of the coating achieved by using a microemulsion.

Source: Reprinted with permission from "Nanostructured surfactant-based systems for the removal of polymers from wall paintings: a small-angle neutron scattering study," M. Baglioni, D. Berti, J. Teixeira, R. Giorgi, P. Baglioni. *Langmuir* 2012, 28: 15193–15202. Copyright 2012 American Chemical Society. (Bottom panel) Left: Detached fresco from the S. Cristoforo church in Milan before cleaning and restoration. Right: The fresco after cleaning with a microemulsion and restoration. Source: "Nanostructured fluids from degradable non-ionic surfactants for the cleaning of works of art from polymer contaminants," M. Baglioni, M. Raudino, D. Berti, U. Keiderling, R. Bordes, K. Holmberg, P. Baglioni. *Soft Matter* 2014, 10: 6798. Reproduced by permission of the Royal Society of Chemistry.

A limitation to the use of aqueous nanostructured cleaning fluids concerns their application onto highly water-sensitive surfaces. This is not usually an issue for wall paintings and stone, but can be problematic when cleaning paper artworks or easel paintings, where the dyes or the color binders are sensitive to water (e.g., acrylic paintings). While nanostructured cleaning fluids can be prepared also by dispersing aqueous solutions in nonpolar organic solvents (w/o), these fluids can exhibit decreased capability of removing soil and in some cases contain higher amounts of surfactants than o/w systems (Ormsby et al. 2016). A possible solution for using o/w microemulsions on water-sensitive surfaces is to confine the fluids within highly retentive matrices, such as those of polymer networks. Traditionally, polymer thickeners such as polyacrylic acid or cellulose derivatives have been used to make networks that are held by secondary bonds (hydrogen bonds, polar forces, Van der Waals interactions) between the polymer chains. These systems allow effective cleaning and reduce the spreading of fluids; however, they tend to leave polymer residues (Casoli, Di Diego and Isca 2014) owing to the lack of strong interactions (e.g., primary bonds) between the polymer chains, which results in poor viscoelastic behavior. Besides, several of these “gel-like” thickeners are not retentive enough to allow the gradual release of loaded aqueous fluids or solutions on water-sensitive substrates such as dyed and inked paper or canvas (Baglioni et al. 2015a). Alternative confining systems have been developed in the framework of soft matter and colloids science. Examples include chemical gels where the polymer network is held by covalent bonds (cross-links) between the polymer chains, and where polymer blends are formed by embedding linear or branched polymers into one or more polymer networks during the polymerization reaction (interpenetrating polymer networks (IPNs)). The composition and degree of cross-linking of the network can be tuned, resulting in different mechanic (viscoelastic) properties, porosity, and affinity to water or polar solvents. This allows the formulation of gels that can be easily handled, applied, and removed from the artistic surface without leaving polymeric residues (for instance as detectable with infrared spectroscopy). Controlling the porosity and

the composition of the gel network also allows tuning of the retentiveness of the gel when it is loaded with aqueous fluids, which grants the safe and controlled treatment of inked paper works and poorly bound painted layers on canvas paintings.

Finally, in cases where the use of aqueous fluids is not convenient, organic solvents can be confined in organogels, which limit the solvents' volatility (and thus their impact on the health of operators) and allow the controlled release of the solvents on artistic surfaces. Recently, chemical organogels based on the cross-linking of methyl methacrylate (MMA) have been used for the first time to remove varnishes from the surface of canvas paintings (Baglioni et al. 2015b). The gels were loaded with solvents with average polarity such as methyl ethyl ketone, cyclohexanone, ethyl acetate, and butyl acetate, which are capable of swelling or dissolving several natural (terpenic resins) and synthetic (vinyl acetate and acrylate copolymers) coatings frequently met in the conservation practice. The loaded gel is applied for a short time to the surface (e.g., for one minute or less), and as a result the coating is either dissolved (and migrates into the gel) or swollen, and then removed with a gentle mechanical action.

Altogether, microemulsions, micellar solutions, and chemical hydrogels and organogels have expanded consistently the palette of tools that are nowadays available to conservators for the cleaning of works of art. However, while the removal of soil and detrimental layers provides aesthetic improvement and prevents further degradation of the artifacts, the cleaned surfaces can still be in need of consolidation as their mechanical properties are worsened by natural aging, weathering, and degradation from detrimental consolidants used in past restorations.

The first solution developed in the framework of colloids and nanoscience for the consolidation of works of art concerned the synthesis of nanoparticles of calcium hydroxide for the strengthening of carbonate-based wall paintings and stone. This approach is alternative to the use of traditional consolidants and adhesives such as acrylate-vinyl copolymers used since the 1960s. In fact, these polymer coatings alter strongly the physico-chemical properties of murals and stone,

with particularly detrimental effects when salts pollute the porous matrix of the artifacts. In such case, salts crystallize between the coating and the artifacts' surface, leading to mechanical stress and to the disruption of the surface layers. The polymer coatings can degrade in turn, exhibiting yellowing and loss of adhesion owing to natural aging. Instead, calcium hydroxide ($\text{Ca}(\text{OH})_2$) is an ideal material for the consolidation of carbonate-based substrates, because it is able to react with atmospheric CO_2 (carbonation process), recreating a network of carbonate within the pores of weakened artifacts, through a process that mimics the setting of a fresco. The newly created carbonate network provides mechanical strength and matches the chemical and physical properties of the original artifacts, minimizing drawbacks in the long term. However, the scarce solubility of $\text{Ca}(\text{OH})_2$ in water hinders the use of aqueous solutions of hydroxide, which exhibit only poor consolidating power. An effective solution was then to disperse $\text{Ca}(\text{OH})_2$ as nanoparticles in nonaqueous solvents such as short-chain alcohols (ethanol, propanol). This allows the direct delivery to the artifacts of higher amounts of hydroxide as opposed to aqueous solutions, with a dramatic increase in the consolidating power. Another significant advantage is that the use of dispersions avoids the presence of a large excess of free, mobile hydroxide ions delivered all at once on the surface, which can be detrimental to alkali-sensitive pigments in the painted layers of the murals. Dispersions of calcium hydroxide nanoparticles have been successfully used in numerous case studies in the last decades (Figure 2), and the best procedures have been set, including practical tips and applicative protocols to maximize the penetration of the particles, favor the carbonation of hydroxide, and avoid the formation of white veils on the treated surface.

The application of the particles is typically carried out after removal of the majority of the salts that pollute the mural or stone; otherwise the presence of some electrolytes (e.g., soluble sulfates) might hinder the consolidation effect. In particular, the consolidation of stone involves some challenging aspects as compared to that of murals, namely the penetration of the particles through the stone matrix can be hindered by several factors, for instance oscillations in temperature and relative humidity can lead to

condensation of water in the pores, which makes particles stack, hindering their homogeneous penetration (Baglioni et al. 2015a).

Dispersions of alkaline earth hydroxides have been also applied since the early 2000s for the pH adjustment of acidic artifacts such as paper, canvas, and wood, as well as for the consolidation of bone and ivory. Acidity sources are various, including pollution gases hydrating in the fibers' moisture, volatile organic acids developed by adhesives and glues used in repairs, and wooden boxes used for storing the artifacts, acidic compounds used in the papermaking process, inks, and the presence of acidic groups in the cellulose chains owing to the oxidative degradation of the objects. In the case of waterlogged wood (e.g., shipwrecks), acidity can also be due to the presence of sulfuric acid formed after salvage, owing to the oxidation of reduced sulfur compounds that accumulated in the wood when it was buried in polluted water with sulfate-reducing bacteria. The presence of iron ions (from corroding bolts and other metallic parts) favors the oxidation of cellulose and the formation of acids. It was shown that the nanoparticles' dispersions can be feasibly applied (e.g., by spraying, brushing, or immersion), and after the evaporation of the solvent the particles adhere to the cellulose fibers, where they undergo carbonation. An alkaline reserve of carbonate is thus formed to prevent the damage of cellulose from the recurring formation of acids in the fibers' network (Figure 3). The application of particles dispersed in a solvent, rather than of free and mobile hydroxide ions in solution, is less risky to oxidized cellulose fibers that are sensitive to alkalinity, making the method safer than traditional baths with aqueous solutions of alkalis.

The treatment of wood can be more problematic than that of paper and canvas because the thorough and homogeneous penetration of the particles through the wood matrix can be hindered by the presence of consolidants such as polyethylene glycol, traditionally used to prevent the shrinkage of waterlogged wood as it dries (Baglioni and Chelazzi 2013). As a matter of fact, different types of particles have been applied on wood since 2007, including calcium, magnesium, and strontium hydroxide or carbonate, and have resulted in effectively neutralizing the acidity and preventing the formation of acids (Chadwick et al. 2014). Besides, as discussed in a review by

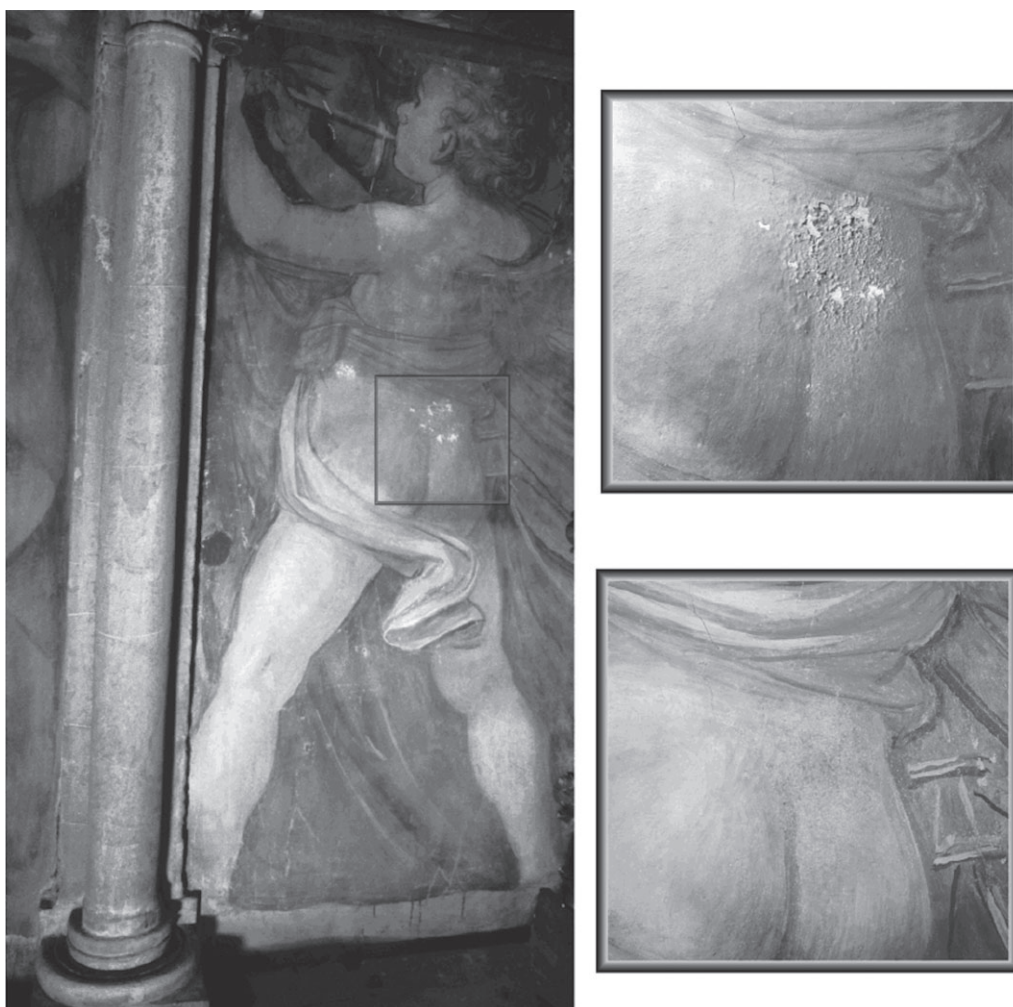


Figure 2 Example of application of $\text{Ca}(\text{OH})_2$ nanoparticles dispersed in propanol during consolidation of wall paintings by Santi di Tito (sixteenth century) “Gli Angeli Musicanti” on the Counterfacade of the Santa Maria del Fiore Cathedral in Florence. The region labeled with the box is that treated with the particles: (top) before restoration and (bottom) after restoration.

Source: Reprinted with permission from “Colloidal particles of $\text{Ca}(\text{OH})_2$: properties and applications to restoration of frescoes,” M. Ambrosi, L. Dei, R. Giorgi, C. Neto, P. Baglioni. *Langmuir* 2001, 17: 4251–55. Copyright 2001 American Chemical Society.

Marzi (2015), various nanostructured materials have also been explored for the protection and reinforcement of timber structures, including clays and oxides used to achieve waterproofing, ultraviolet (UV) protection, biocide, fire resistance, self-cleaning, and anti-scratching properties.

Recently, nanomaterials such as microemulsions, gels, and nanoparticles have been used for

the first time on collaged-based substrates. In particular, historical leather was cleaned from soil and patinas using hydrogels loaded with o/w nanostructured cleaning fluids, and then the pH was adjusted to values that are typical of pristine leather, in order to prevent the acid hydrolysis of collagen (Baglioni et al. 2016).

While much work has been done on the preservation of classic works of art, efforts are currently

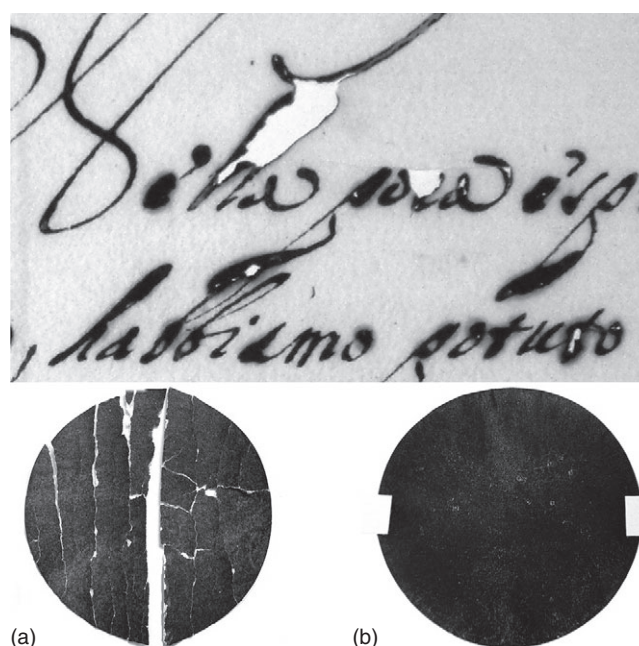


Figure 3 (Top panel) Corrosion of paper due to presence of iron gall inks on a historical manuscript. (Bottom panel) Inked paper samples after accelerated aging: (a) an unprotected sample and (b) a sample treated with nanoparticles to protect it from aging. Replica samples were made by application of iron gall ink on 99.9 percent cellulose unsized Whatman paper.

Source: Reprinted with permission from “Colloid and Materials Science for the Conservation of Cultural Heritage: Cleaning, Consolidation, and Deacidification,” *Langmuir* 2013, 29: 5110–22. Copyright 2013 American Chemical Society.

being dedicated to addressing the conservation of modern and contemporary artifacts, which exhibit different degradation processes that can be often sudden and highly detrimental. Numerous modern and contemporary artifacts have been realized using materials derived from the industry, which were not meant to last long, and whose complex composition poses challenges to the effective preservation of the objects. Current conservation topics involve the cleaning of modern paintings, plastics, and metals, and the strengthening of both surface layers and supports (e.g., canvases).

SEE ALSO: Characterization of Pigments; Chemistry in Archaeology; Community Heritage; Conservation; Conservation Documentation; Conservation of Bone, Horn, and Ivory; Conservation of Earthen Building Materials; Conservation of Metals; Conservation of Polychrome Natural and Architectural

Surfaces; Conservation of Waterlogged Materials; Conservation Science; Grouting in Conservation

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Neutron Imaging and Tomography in Conservation

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An introduction to neutron imaging

Neutrons are subatomic particles with no overall charge; they were discovered by James Chadwick in 1932 and, together with slightly smaller, positively charged protons, make up the atomic nucleus. Neutron imaging is a radiographic technique in which a beam of neutrons is applied to an object (see NEUTRON RADIOGRAPHY AND TOMOGRAPHY). The manner in which the neutron beam is attenuated by the object allows its internal structure to be recorded (Ryzewski et al. 2013, 344). The technique was first developed in the 1930s and 1940s by Hartmut Kallmann and Ernst Kuhn; it was refined by J. Thewlis in the 1950s and continues to evolve to this day (Brenizer 2013, 11). Over the past decade the potential of the technology has rapidly advanced, owing to improved computing facilities and new, more sensitive techniques and sensors. It can be used in both 2D and 3D (tomography) for detailed exploration of objects.

Neutron imaging is a powerful, nondestructive method of object investigation developed primarily for industrial purposes, including for the investigation of nuclear fuel and for aerospace engineering. From the 1970s, its potential contribution to the field of cultural heritage studies has slowly started to be recognized. Its capacity to extract detailed information about the internal structure of an object has important ramifications for conservation, enabling the development of more targeted, individually tailored approaches to treatment. It can then be used for continued monitoring and assessment of the success of treatments applied. However, there are also certain risks and limitations of neutron imaging that

must be considered when evaluating its possible role in any given program of conservation.

The benefits of neutron imaging

A nondestructive investigative technique

For conservators, the primary benefit of imaging techniques for the investigation of objects is the fact that these methods are noninvasive and nondestructive. The physical integrity of the object need not be compromised by the removal of samples. Furthermore, imaging a whole object allows it to be assessed in its entirety, while sample analysis provides definitive information only for that small piece.

Different imaging techniques can be adopted for different purposes. For example, methods using visible light, such as 3D laser scanning and reflectance transformation imaging, can facilitate close investigation of the external morphology of an object and its surface texture (see LASER SCANNING AND REFLECTANCE TRANSFORMATION IMAGING (RTI) IN CONSERVATION). Methods involving other, more penetrative forms of radiation, such as neutrons and X-rays, can facilitate the observation of the internal structure. When used together, these techniques allow comprehensive visualization, recording, and analysis of the entire composition and construction of an object. Visible light techniques are becoming increasingly sophisticated and accessible, and X-ray radiography (see X-RAY RADIOGRAPHY) has long been used by conservators for the exploration of the internal structure of objects. Neutron imaging has been much less widely adopted but can represent a valuable complement to X-ray radiography, providing a superior method of imaging for certain types of material.

A complement to X-Ray radiography

An X-ray or neutron image displays the extent to which radiation has penetrated an object. A beam of radiation is applied to the object, behind which is a photosensitive film or digital detector;

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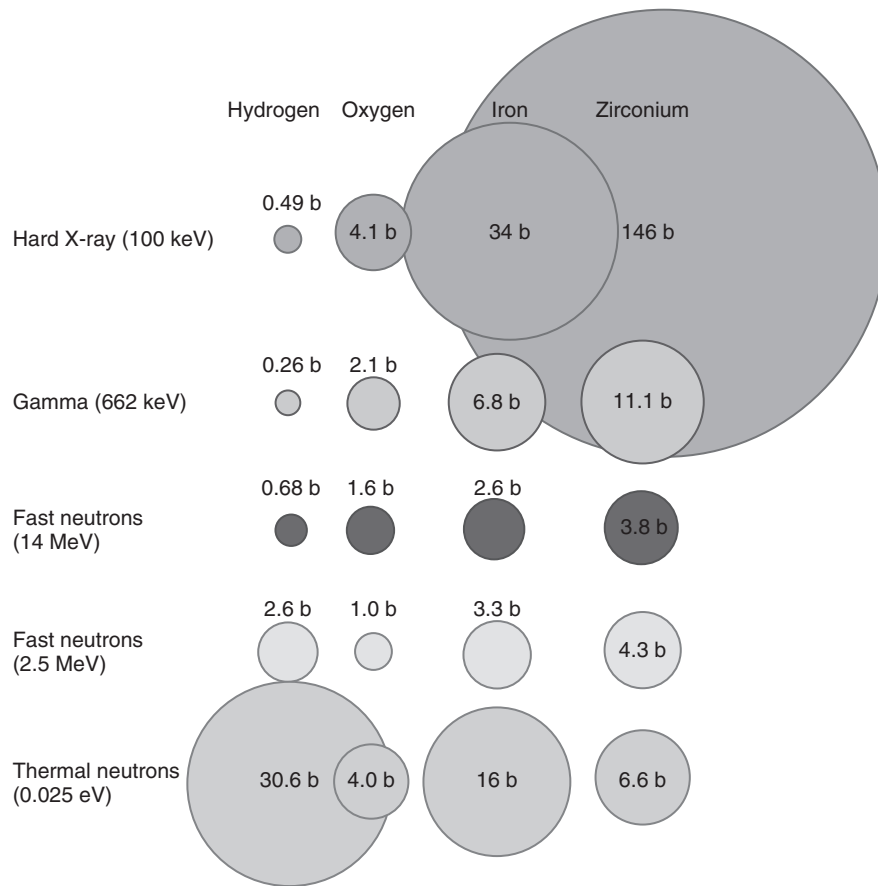


Figure 1 A visual representation of the total microscopic reactions between different elements and different types of radiation applied using tomographic probes. Republished with permission of the author, Andersson, P. 2014. “Fast-Neutron Tomography Using a Mobile Neutron Generator for Assessment of Steam-Water Distributions in Two-Phase Flows. Digital Comprehensive Summaries of Uppsala Dissertations from the Faculty of Science and Technology 1146. Uppsala: Acta Universitatis Upsaliensis.

this records any radiation that has successfully passed through the object. In these images, bright white areas indicate the presence of materials penetrated only to a very limited extent; darker areas signify materials that are more transparent to the radiation applied. However, neutrons and X-rays interact differently with the component parts of any given object. Whereas neutrons interact with atomic nuclei, X-rays interact with the electron cloud (Ryzewski et al. 2013, 344). The diverse nature of these interactions means that neutron and X-ray beams are attenuated to different degrees when applied to the same materials (see Figure 1).

Unlike X-ray radiography, neutron imaging can provide clear distinctions between different isotopes and between elements in close proximity on the periodic table. Moreover, neutrons are typically very good at passing through materials, which are relatively opaque to X-rays, and vice versa. The radiodensity of an object—the extent to which X-rays can pass through it—is connected to both the density and the atomic weight of its composite materials: as density and atomic weight increase, so does radiodensity. This principle does not apply to neutron imaging. While X-rays can easily penetrate materials, including organics, composed from lighter elements, neutrons can

be readily scattered and absorbed by many such elements, including hydrogen, carbon, and nitrogen. Conversely, unlike X-rays, neutrons can easily penetrate layers of dense metal. This behavior of neutrons—their passing through some materials while being absorbed or scattered by others—varies according to their energy. Fast-moving neutrons supplied in a high-energy beam can pass through most materials with ease. For object analyses, it is typically most useful if they can pass relatively easily through metals while being significantly attenuated by light elements. To achieve this, neutrons can be cooled: this reduces their speed and penetrative capacity.

Both X-rays and neutrons can be harnessed to capture 2D images; however, tomographic imaging can also be employed. Tomography is the imaging of the internal structure of objects in section: both computed tomography (CT) scanning, which employs X-rays, and neutron tomography (NT) involve taking a series of cross-section images at multiple, evenly spaced orientations by revolving the radiation beam and the digital detector around the object. The cross-sections are reconstructed to create a 3D model from which cross-section slices (tomograms) can be extracted for analysis (Ryzewski et al. 2013, 345; see X-RAY TOMOGRAPHY and COMPUTED TOMOGRAPHY).

Current uses in conservation

Neutron imaging represents a powerful tool for conservators for a number of important reasons. It is nondestructive and noninvasive, allowing in-depth analysis of the structure and composition of object interiors without the need for sampling. The complementary characteristics of X-ray radiography and neutron imaging mean that conservators may profitably use these two techniques together, or a single technique might be selected if an object is particularly suited to one type of imaging. For example, neutron imaging is very useful for the investigation of organics and hydrogenous materials, for metallurgical studies, and for exploring composite objects comprising substances with low atomic numbers contained within materials with high atomic numbers. This includes organics found within metallic or stone

matrices; and also waterlogged ceramics, leather, and wood. X-ray radiography is of limited use in such cases, since the heavier materials block the view of the lighter ones. These benefits of neutron imaging have made the technique an increasingly attractive option for the investigation of heritage objects before, during, and after conservation treatment.

Before commencing any conservation treatment, neutron imaging can be used as an investigative technique to address technical questions, such as determining the methods of manufacture used to create a given object and the range of craft skills necessary for its production. The answers to these questions can provide valuable insights into the technological capabilities and concerns of a particular society. Neutron imaging is particularly appropriate for investigations centered on distinguishing heterogeneous constituents within metallic artifacts. Therefore the technique can play an important role in compositional and provenience analysis. It can also be used for the detection of organic remains found within closed metal artifacts (e.g., shrines or casks) and for finding the remnants of clay molds on cast-iron objects (Rant et al. 2006, 8). Such information is valuable to archaeologists and conservators alike. As well as providing details of the raw materials and creative processes involved, neutron imaging can help to reveal the behavior of these component materials and the current condition of the object. A condition analysis might include, for instance, the detection of structural flaws, the extent of metal corrosion, and the presence of soluble salts or old restorations. Understanding the condition of an object is essential for both archaeologists and conservators. For the archaeologist, the condition may provide clues as to the function of an object and how it was used and valued over time. These details help the conservator to gain a full understanding not only of the problematic aspects of condition that require specialist intervention, but also of the historical significance of the object: combined awareness of both strands is crucial for an appropriate conservation strategy to be determined.

A conservation strategy will typically involve both preventive and remedial measures. The former might include housing the object in an appropriate, climate-controlled environment, if neutron imaging were to discover the presence

of soluble salts. Neutron imaging might also help guide the handling and packing of objects or the application of remedial measures, for example the introduction of resins for consolidation, based on the pinpointing of any structural flaws. After an initial assessment and the commencement of a conservation strategy, neutron imaging can then be employed to continue to monitor the extent of corrosion or salt issues, to ensure that cracks remain stable, and to evaluate the success of applied remedial treatments. Oils, waxes, and resins—materials used for consolidation treatments—contain high levels of hydrogen to which neutron imaging is particularly sensitive.

Notable recent studies include Krejci et al.'s (2016) research at the Institute of Experimental and Applied Physics, Czech Technical University (Prague). One case assessed the use of neutron imaging to analyze a Roman leather shoe. Neutron imaging enabled detailed analysis of this composite object, clearly showing that the shoe was constructed from several layers of leather and contained iron studs. Lehmann, Vontobel, et al. (2005) conducted neutron imaging of a Roman bronze statue of Mercury from Thalwil (Swiss National Museum, Zurich). This object is composed of thick layers of metal: neutron imaging successfully enabled its structure to be analyzed, while X-ray imaging of the same object produced little information.

Rehren et al.'s (2013) study involved ancient Egyptian iron beads (Petrie Museum of Egyptian Archaeology, UCL, London), which were analyzed at the Budapest Neutron Centre, Hungary. These beads were heavily corroded and their structure was unclear from visual analysis. Neutron imaging revealed the tubular nature of the beads: they were discovered to have a central hole along the long axis—this was now filled with corrosion products but would once have been used for stringing. The images also showed that the beads were constructed from rolled-up iron sheet, and, although badly corroded, the analysis demonstrated that their original structure was preserved (see Figure 2).

The use of neutron imaging to assess the presence of consolidant has been illustrated by Lehmann, Vontobel et al. (2005). Neutron imaging successfully detected consolidant within a knife from the Roman site of Vindonassa (Switzerland); X-ray radiography, by contrast,

had revealed only empty space. Lehmann, Hartmann et al.'s (2005) research has also shown that, in addition to displaying the final distribution of the applied consolidant, neutron imaging can be employed to compare the uptake behavior of various consolidants and solvents when applied to wooden artifacts. Osterloh and Nusser's (2014) work has similarly adopted neutron imaging to investigate the presence of old restoration treatments. In this case, the analysis centers on the use of "carbolineum," a hydrocarbon-based consolidation treatment often employed in the early twentieth century to stop the biological decay of wooden sculptures. This was a noxious material, causing dark staining; it is no longer used by conservators and it is desirable that, where possible, it should be removed from treated objects. Neutron imaging can help assess the distribution of carbolineum and the extent to which it has penetrated the objects to which it was applied; this enables a better assessment of the feasibility of its removal.

Limitations and risks of neutron imaging

The equipment required for neutron imaging is different and, currently, more expensive, more complex, and more hazardous than the one needed for X-ray radiography. The absorption of neutrons from the neutron beam by the nuclei of the constituent atoms of the target object can produce short-lived radioactive isotopes. The length of time for which an object remains radioactive depends on the intensity of the neutron source and on the length of exposure (Rant et al. 2006, 9). It may not, therefore, be immediately safe for an object to be returned to its collection. The Oak Ridge National Laboratory (ORNL) Neutron Sciences Directorate has developed a sample activation calculation (SAC) tool to estimate an object's neutron activation after exposure to a neutron beam. A balance must be struck between the use of a sufficiently intense beam for imaging and making sure that the object does not remain radioactive for an inordinately long spell of time. The aim of the SAC is to ensure that objects can safely be returned to their collections within a year (Ryzewski et al. 2013).

In order to prevent objects from remaining radioactive for lengthy periods and to allow a

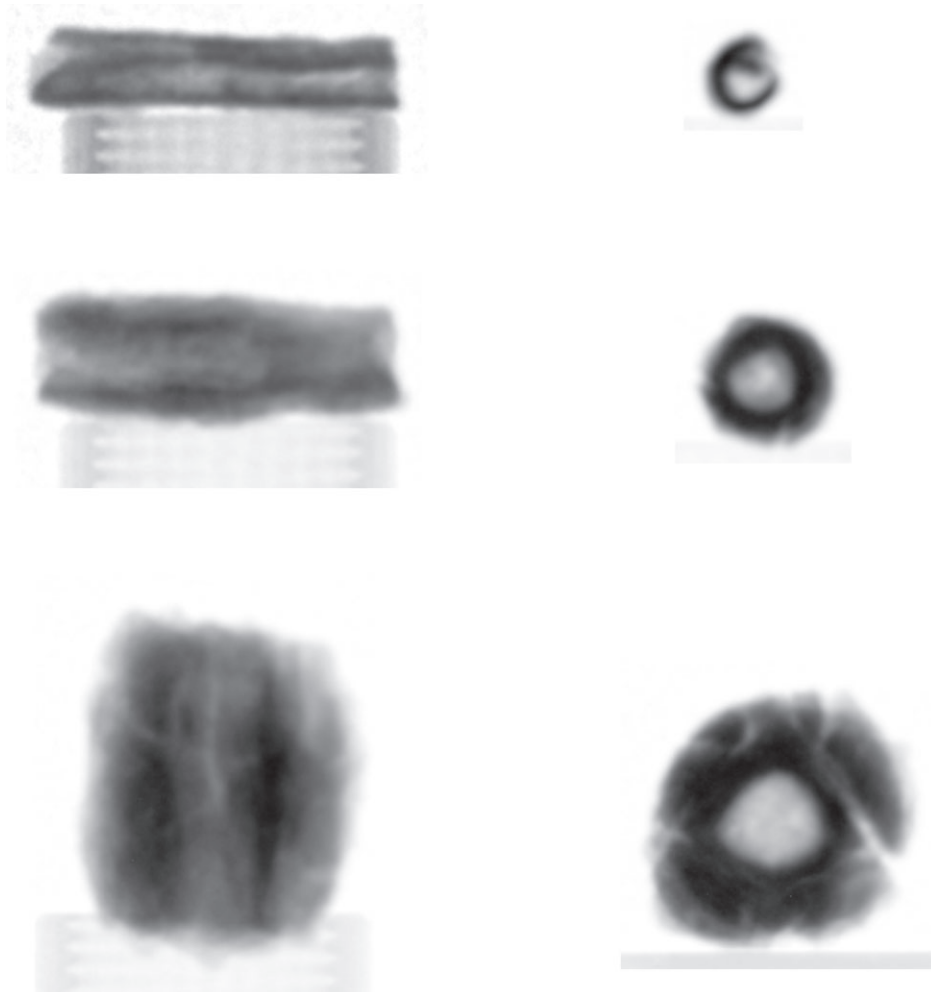


Figure 2 Neutron images of iron beads, in side view (left) and perpendicularly (right). Petrie Museum UC10740, UC10739, and UC10738 (from top). Republished with permission of the authors, Rehren et al. 2013. “5,000 years old Egyptian iron beads made from hammered meteoritic iron.” *Journal of Archaeological Science* 40: 4785–4792.

clear distinction between easy penetration of metals but widespread scattering and absorption caused by the abundance of lighter elements such as hydrogen and carbon, the neutron beams employed for analysis are typically rather less intense than those produced from X-ray sources. This means that it is difficult to obtain high-resolution images (see Figure 3). Moreover, while neutron imaging is well suited to the analysis of metallic, organic, and composite objects, there are materials for which it is of rather limited use. For instance, the constituents

of ceramic objects do not provide great contrast in neutron imaging; however, the technique remains useful for detecting the presence of other materials, such as organic residues or restoration treatments (Rant et al. 2006, 8).

Archaeologists and conservators may find it difficult to locate a suitable neutron imaging facility. Naturally, such facilities require a neutron source and, as a result, have typically been associated with nuclear reactors. These facilities are few and far between, especially when contrasted against the ubiquity of the X-ray

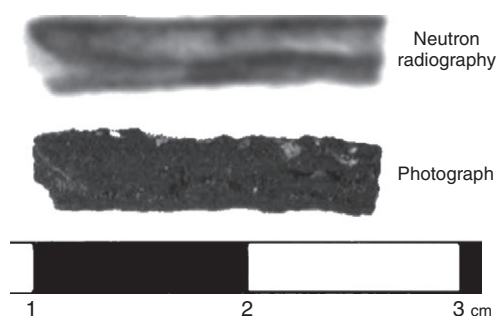


Figure 3 Photograph and neutron image of an iron bead (Petrie Museum UC10740).

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machine. A significant issue for conservators is the transportation of often fragile objects to a distant imaging facility.

State of the field and future developments

The digital revolution has had a significant impact on neutron imaging. The first neutron images were created using photographic film; however, charged-couple device (CCD) cameras are now widely used to produce digital neutron images. The digitization of these images has enhanced the quantitative powers of their analysis: grey values can be quantified and pixels counted. Image resolution is also being improved—the development of increasingly sensitive detectors with large fields of view means that better images can be produced while using a beam of the same intensity (Krejci et al. 2016).

Neutron imaging facilities remain relatively scarce, but are steadily growing in number. The United States has five facilities, while the United Kingdom has just one—the ISIS facility at the Rutherford Appleton Laboratory in Didcot, near Oxford. There are other facilities scattered elsewhere in Europe: one in France, one in Belgium, four in Germany, two in Switzerland, one in Austria, one in Slovenia, one in Poland, one in Hungary, one in Romania, one in Greece (under construction), one in Norway, one in Portugal. Other countries with facilities are

China, Egypt, Algeria, South Africa, Brazil, Argentina, Morocco, Israel, India, Bangladesh, Thailand, Indonesia, South Korea, Japan, and Australia. The International Society for Neutron Radiology provides up-to-date information on available facilities and organizes conferences and workshops. Freely available instructions are provided for the construction of a simple computed tomography system for basic testing. This still requires access to a neutron source. However, more mobile equipment is being developed (Rant et al. 2006, 8; Arai and Crawford 2009). Therefore the technique continues to become more widely accessible and offers an increasingly precise image analysis.

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Photoluminescence of Egyptian Blue

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The synthetic pigment called Egyptian Blue has its counterpart in the natural mineral cuprorivaite, with a formula $\text{CaCuSi}_4\text{O}_{10}$ (Minguzzi 1938). The time and location of EB first synthesis are not known. Corcoran (2016) identified the earliest known example of EB, on a bowl dated to 3250 BCE. The pigment found its larger application in Egypt of the New Kingdom and the Fifteenth dynasty, and subsequently in the Greco-Roman culture where it was used extensively on mural paintings, polychrome statues, and was even used for solid mosaic tesserae. If we think of EB as a compound with a definite crystal structure, its composition is perfectly defined and the ratio between its components corresponds to the stoichiometric formula. The X-ray refinements of a modern synthesized crystal and one found in a Roman archaeological excavation in Aosta are identical within a standard deviation (Mirti et al. 1995). If, on the other hand, we consider EB as the pigment in its complexity as it is used, we may find substantial differences from one case to another, mainly due to the only approximate stoichiometry of the mixes (silica, lime and copper) originally used. Since the silica fraction tends to be in excess, a glass phase is almost always present in the form of the so-called Egyptian Green. The raw materials are also different from place to place, including copper mineral, copper slags or bronze scrapings (in this case, the presence of tin or lead can be the marker). EB was also used in Egypt to make small molded statues or amulets by sintering the fine powder in a mold at high temperature. It is commonly believed that the technology of EB was lost in Western Europe after the fall of the Roman Empire. However, sporadic findings, one dating to the twelfth century (a Last Judgment by Nicolaus Joannes in the Vatican Museum) and a Madonna by Giovanni

Benvenuto dating from 1524 (Bredal-Jørgensen 2011), among others, suggest that somewhere its production continued.

The luminescence of EB is so strong that recently it has found an application in forensic science to detect fingerprints. Discovered in 1996, this luminescence was exploited with success by Giovanni Verri in 2006, who set up the first equipment for imaging EB. A single very small crystal of the order of a few microns can easily be visualized using the technique of visible induced luminescence (VIL). Therefore, in the case that there is some doubt in the attribution of a marble statue to the Greco-Roman period or to the Renaissance, the finding by VIL of a few EB crystals not visible to the naked eye may indicate that the art object belongs to the older period. Future research is certain to expand the temporal range of EB, both by looking for earlier applications and by documenting its use in later paintings throughout Europe.

The VIL technique and equipment

EB is blue in reflected visible light, and therefore has its maximum absorption in the red region, at 637 nm as measured by Accorsi et al. (2009). It reemits energy by luminescence at 910 nm. VIL imaging consists of picking the luminescence signal in the near infrared, having removed all possible interferences. For this purpose digital cameras are used, equipped with a charge coupled device (CCD) obviously sensitive to all visible light (they are built for this purpose). Normal cameras have a short-pass filter in front of the CCDs that cuts out the undesired IR radiation in regular photography. That filter needs to be removed for VIL applications, and specialized photography stores can do this for a fee. On the Internet there are also detailed descriptions of how to reach that filter, if one wants to be brave. Once the IR radiation can reach the CCD, the problem remains of eliminating visible light, which is orders of magnitude more intense than the VIL signal. The solution consists of screening

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the CCD with a long-pass filter that cuts out the visible light but lets the IR signal go through. An appropriate filter should have the absorption edge around 830 nm. Once visible light is eliminated, the further problem remains that some IR radiation may be present in the environment and reflected by the object under examination. In order to capture the VIL signal as clearly as possible, so that it can be attributed to EB luminescence only, one needs to eliminate as much as possible the parasite IR. This IR radiation may be generated by the light source used for the excitation, or be part of the environment. This problem can be solved in two ways, both routinely applied: (1) by eliminating or reducing the effect of the environmental IR, for example by operating in a dark room; (2) by strongly increasing the VIL signal compared with the background, using a much more powerful excitation source. In a studio environment where no ambient IR is present, a source without an IR component (e.g., LEDs of various wavelengths) can be selected, favoring the red ones because of maximum absorption. In the case of sources containing IR, this can be filtered away using short-pass filters (750 nm being appropriate). For the environmental IR pollution the problem cannot be solved using filters, since the wavelength of the VIL signal and that of the light reflected by the object are in the same range. However, VIL may not always be carried out in a dark room, as often there is the need to image non-movable objects in daylight. In this case, increasing the excitation power by using, for example, camera flashes properly filtered to remove the IR component is an adopted solution. The stronger excitation increases the VIL signal-to-background ratio, thus making it possible to perform a proper VIL. The excitation depends on the power of the source and on the inverse square of the distance from the object. It is therefore useful to use more than one synchronized flash and to locate them as close as possible to the object under examination. If one needs to image a large surface in daylight, the use of more than one flash is mandatory. Obviously the IR radiation reflected by the environment is still present, and even parts of the object that do not contain EB show a faint ghost image. This can be dealt with in the image post-treatment.

Images post-treatment

VIL images that show only EB luminescence are rare, being those obtained in a dark studio room using an excitation source totally absent of IR radiation. In the majority of cases VIL imaging is carried out in museums, archaeological sites, or in general in the presence of IR light (see Figures 1 and 2 for examples). This is reflected by the object and cannot be filtered out since it is very similar to the VIL signal. Normally this is dealt with by inserting a non-emitting standard in the image field (but the parts of the object not containing EB can be effectively used as a standard), together with a VIL-emitting standard (normally homemade objects containing EB in various concentrations). Many image-treating programs are available to transpose the image in black and white and then, using the histogram function or the combination of brightness and contrast, evidence the VIL signal. It is highly advisable to take a visible image of the object exactly from the same spot as the VIL one, using a similar camera and the same focal length to avoid distortions. The two images can then be rectified and perfectly superposed and even cross-faded. This series of operations is particularly useful when the amount of EB is small and therefore it is not easy to establish exactly where it is located. The final image so obtained can be effectively compared with other images of the same object, such as by radiography, electron emission, UV and other multispectral images, or the IR image. This exercise gives a large amount of information for the piece of art under examination.

The advantage of VIL with respect to other types of imaging is that VIL is the most sensitive and specific for EB. Although obviously it is always useful to perform other non-invasive analyses as a verification, VIL may not require it. The IR signal penetrates through various types of patinas, including dirt and deteriorated varnishes, thus detecting EB even when it is not visible at all. This was very useful in reading painted inscriptions on sarcophagi that were completely obliterated by the overlying material. In certain instances, EB is mixed with other pigments in order to produce different colors. In these cases, VIL is useful in detecting EB even

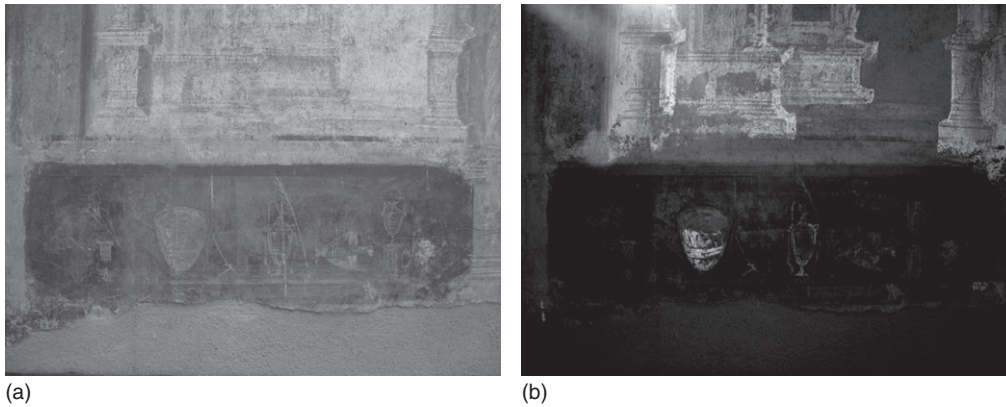


Figure 1 (a) Visible and (b) VIL images of a small section of wall painting from the Casa degli Augustali in Herculaneum. Notice the use of adding EB to the white to make it appear brighter. Many more details of the decoration are detectable in the VIL image. Photos: G. Chiari.

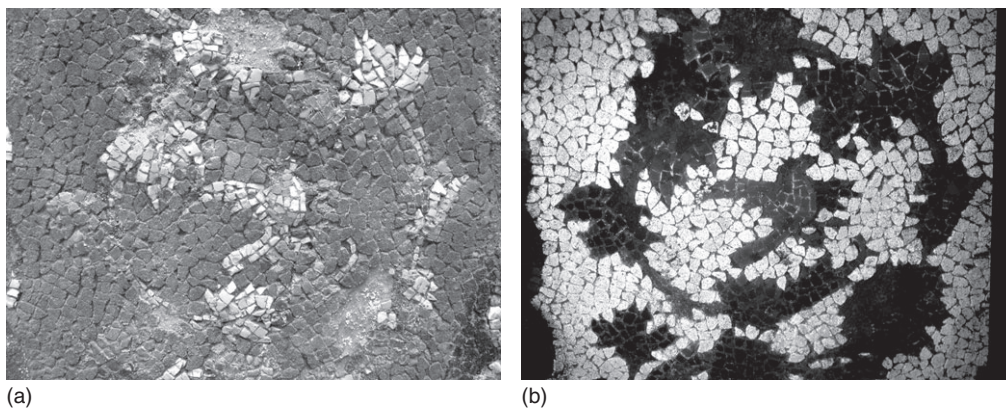


Figure 2 House of Neptune and Amphitrite in Herculaneum. (a) Nymphaeum, imaged in visible light. The centimeter-sized tesserae are made of solid EB. (b) The VIL was performed in daylight using two flashes with a blocked IR component. Photos: G. Chiari.

when the color of the surface is totally different from blue. We now know that the majority of ancient statues were polychrome, but the predilection for white surfaces on marble statues in the past centuries and the consequent zeal in thoroughly cleaning them have left hardly any trace of pigments. Even a few crystals of EB can prove the presence of an ancient polychromy and thus is useful in authenticating an object.

In conclusion, the ability to exploit the peculiar luminescence of EB when excited by visible light gives conservation scientists an extremely

powerful imaging technique which has found valid applications in several domains of heritage investigation.

SEE ALSO: Imaging; Multispectral and Hyperspectral Imaging of Artworks

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FURTHER READINGS

Pigment Alteration

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Pigment alteration occurs following a chemical reaction or a physical phase change which often, but not always, changes the color of the pigment. While there are many chemical reactions that can occur among pigments, the environment, and binding media, the term pigment alteration refers to a physical change in the appearance of the pigment. There are many different causes for pigment alteration, and some pigments are inherently less chemically stable and more prone to chemical modifications than others: Only a few inert pigments exist. Indeed, the conservation of polychrome and archaeological surfaces (see CONSERVATION OF POLYCHROME NATURAL AND ARCHITECTURAL SURFACES) often involves the documentation and study of pigment alteration, a major challenge for conservation science (see CONSERVATION SCIENCE). The environment and the combined effects of relative humidity, temperature, radiation, and air pollution (see AIR POLLUTION) play major roles in pigment alteration.

Pigment sensitivity to light and heat is attested by historical treatises, but the chemical modifications that are responsible for pigment alteration are the current focus of advanced analytical chemistry: Pliny the Elder in *Natural History* warns of the instability of vermilion (αHgS) to light and its tendency to darken, and Vitruvius in *The Ten Books on Architecture* infers the heat sensitivity of lead white (basic lead carbonate, $2\text{PbCO}_3 \cdot \text{Pb(OH)}_2$). Other treatises describe the darkening of pigments which may occur if they are applied in inappropriate media; for example, Cennino Cennini in his *Book of Art* warns against the use of red lead and lead white, neither of which can be used in fresco painting as they will darken in the alkaline lime medium. The darkening of vermilion and lead-based pigments is easily

recognized by eye, so this type of deterioration is often used to identify their presence.

Given specific chemical conditions (including environmental pollution, exposure to heat, visible and ultraviolet radiation, environmental pollution, and reactive ions of chlorine and sulfur), most pigments can degrade and alter in color. Research has also demonstrated how relative humidity and the role of the binding medium in a paint layer can play a crucial role in the stability of pigments (Saunders and Kirby 2004).

Evidence of pigment alteration

There are numerous documented cases of pigment alteration on wall paintings and the deterioration of polychromy, paintings and monuments, excavated sites and artifacts, and some examples are given in the text below. Wall paintings are particularly susceptible to alteration due to their constant interaction with the environment.

Heat-induced pigment alteration is common and many pigments will change color following firing: Indeed, a bright red pigment can be produced by burning yellow ochre. Heat-induced changes to pigments based on iron oxides leads to the modification of their color. Yellow ochre pigments (based on the mineral goethite, $\alpha\text{-FeOOH}$) alter to red hematite $\alpha\text{-Fe}_2\text{O}_3$ if heated above 300°C . The blue pigment azurite $\text{Cu}_3(\text{CO}_3)_2(\text{OH})_2$ and the green mineral malachite $2\text{CuCO}_3 \cdot \text{Cu(OH)}_2$ react to form the black CuO (tenorite).

Cases of fire damage and subsequent pigment alteration have been reported both for excavated sites and for wall paintings. For example, fires in the Minoan site Phaistos (Crete, Greece) are responsible for the change in the color of the walls of the palace. The altered ochre pigments of the buried Emperor Qin Shi Huang's Terracotta Sculptures (Xi'an, China) have been ascribed to the looting and burning of the tomb shortly after its construction in 209–210 BCE (Blänsdorf and Yin 2006). Fires lit within caves on the Silk Road in the Mogao grottos have also provoked

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different pigment alterations; white pigments based on basic lead carbonate $2\text{PbCO}_3 \cdot \text{Pb}(\text{OH})_2$ have reacted to form the brown lead dioxide (plattnerite, PbO_2). In other cases, red lead (Pb_3O_4) may either degrade to form the white pigment cerussite (lead carbonate, PbCO_3) or darken to PbO_2 (Yang et al. 2016). Due to their heat sensitivity, the Romanesque wall paintings from the Chapter House in Sigena (1196–1208) appear monochromatic: the paintings were in a church which was burned in 1936.

While temperature-induced alterations are common, other chemical reactions may occur due to the combined effects of high relative humidity, biological activity, and light exposure. For example, paintings by the Italian Cimabue in the Basilica of Saint Francis of Assisi (Assisi) in 1280 present one of the most famous cases of lead-based white and red alteration on wall paintings: the faces and bodies of many of the figures once painted in highlights are now dark brown, ascribed to the formation of plattnerite.

Light-induced alterations of pigments and dyes may result in fading (for example bleaching or photo-oxidation of indigo and other dyes (see MICROCHEMICAL TESTS IN CONSERVATION)). Red lake pigments which are formed following the precipitation of a dye and a mordant are well known to oxidize and lose their color following exposure to light. Oxidation is particularly problematic for unstable modern lake pigments including eosine or Geranium Lake, and Brazilwood (see DYES). Light exposure can also result in a change in color for inorganic or mineral pigments. For example, realgar (orange) which may alter to form χ -realgar and pararealgar (pale yellow) and examples of alteration of the pigment are common in Egyptian artifacts and works on papyrus (Daniels and Leach 2004). The photosensitivity of HgS has been linked to the presence of Cl^- impurities in the natural mineral (see CHARACTERIZATION OF CERAMICS), and recent work has highlighted multiple mechanisms for degradation of the pigment including photoactivation and the presence of elemental Hg as a by-product of chemical reactions which may cause the darkening of the pigment (Da Pieve et al. 2013; Neiman et al. 2015). Other cases of color alteration include the darkening of the modern pigment chrome yellow which is particularly sensitive to visible light. Research

has demonstrated how the coordination and oxidation of chromium may change and cause a darkening of the pigment, as documented in paintings by Vincent van Gogh and other Post-Impressionists (Monico et al. 2013).

Another important mechanism for pigment alteration is the reaction of pigments with ions that include the formation of oxalates through oxalic acid attack (leading, for example, to the formation of calcium oxalate and copper oxalate), or the formation of sulfates and other sulfur-based pigments, for example the conversion of calcium carbonate to gypsum, or the alteration of lead white to galena (PbS). Chloride ions can also attack many metal oxides, sulfides, and carbonates. For example, the red pigment α -HgS (synthetic vermilion or the mineral cinnabar) has been shown to react with atmospheric Cl^- to form calomel (Hg_2Cl_2) a gray-white pigment, while α -HgS can also undergo a phase modification to β -HgS (metacinnabar), turning black (Nöller 2013). An example of a coordination change which may result in loss of color is smalt—a synthetic blue potash silicate pigment containing cobalt which is well known for its propensity to fade following a change from tetrahedral to octahedral coordination of the trapped Co^{2+} ions (Robinet et al. 2011).

Chloride-based compounds are well-known corrosion products on metal artifacts and may also be associated with the alteration of copper-based carbonate pigments such as azurite (blue) and malachite (green), which react to form atacamite and paratacamite ($\text{Cu}_2\text{Cl}(\text{OH})_3$) (Dei et al. 1998). In other cases, lead white may react to form white alteration products (including lead chlorides, sulfates, and oxalate) (Kotulanová et al. 2009).

The reaction between pigment and binding media may cause the formation of complexes and even the formation of soluble or slightly soluble metal soaps, which has been a major focus of research since the 1990s (see PIGMENTS AND BINDERS). For example, zinc- and lead-based carboxylates are commonly found in twentieth-century paint formulations, either as additives to paint formulae or because carboxylates form as a degradation reaction between fatty acids in binding media and the alkaline pigment. The role of carboxylates in the conservation of

easel paintings is of significant concern and a major area of future research.

Measuring pigment alteration

The detection of pigment alteration, causing a color change, can often be made by the naked eye, but analysis is usually required to confirm degradation products and phase transformations or to monitor the distribution, oxidation state, and mechanisms of pigment alteration. Many advances have been made in understanding the complexity of pigment deterioration and the resulting pigment alteration on the micrometric scale using combinations of microscopy and spectroscopy (Neiman, Balonis, and Kakoulli 2015).

The analysis of color change using analytical imaging and reflectance measurements can provide immediate evidence of pigment alteration, and fiber optic reflectance spectroscopy is one of the most common methods for documenting or monitoring deterioration. Colorimetric spaces may be used to measure change difference in chromatic values which may be related to darkening, lightening, or a modification of a pigment hue. Optical microscopy (see OPTICAL MICROSCOPY) and the observation of cross-sections with scanning electron microscopy (see SCANNING ELECTRON MICROSCOPY) is central to the study of pigment alteration, but is usually combined with other analytical methods for the identification of degradation products and the elucidation of degradation mechanisms. For example, X-ray diffraction (see XRD AND MATERIALS ANALYSIS) (XRD) is sensitive to changes in the chemistry of crystalline phases of pigments and has been widely used to follow degradation; most recently, analysis with a microscopic scale resolution has allowed the mapping of pigment alteration to specific layers of paint cross-sections through the use of synchrotron-based microanalysis (see SYNCHROTRON-BASED X-RAY ANALYTICAL TECHNIQUES AND MATERIALS ANALYSIS) (Da Pieve et al. 2013). On the micrometric scale, the oxidation state of pigments and the coordination of atoms studied by X-ray absorption near edge structure (XANES) (see X-RAY ABSORPTION SPECTROSCOPY (XAS, EXAFS,

XANES)) and their crystal structure with XRD (see XRD AND MATERIALS ANALYSIS) together with molecular spectroscopy (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)) have been critical in the study of the degradation of many pigments including smalt, chrome yellow, vermillion, and cadmium-based pigment (Robinet et al. 2011; Monico et al. 2013; Nieman et al. 2015).

There are no universal techniques for detecting and studying pigment alteration, due to the complexity of paint and the unanswered questions regarding the role of the binding media on the instability of pigments, and the interactions that may develop between different pigments in the same or in adjacent pigment layers. Migration of degradation products through paint and the accumulation of alteration products on the surface of paintings are of current interest. Although it is chemically possible to reverse color change in some cases, it would be unethical to treat them (see ETHICS IN CONSERVATION). Research continues to focus on the role of the environment on deterioration, complex interactions between binders and pigments and the formation of carboxylates or metal soaps, and the degree to which pigment alteration can be prevented.

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Polymers in Conservation

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A wide range of polymers are used in conservation for three main purposes: as adhesives, consolidants, and surface coatings (varnish). Currently used materials with a history of application in the field have been listed along with their general properties (Horie 2010), detailed aging properties, and applications (Down 2015). Their use in conservation dates back to the profession's earliest days, starting with biopolymers, and traces their chemical modification in the nineteenth century and into the early twentieth when synthetic polymers were first commercially available. All three types—natural, semisynthetic, and synthetic—are actively used by conservators in an effective manner. Their intrinsic properties and economic feasibility also account for their use in commercial applications demanding much larger quantities. The impetus for making specific polymers is typically driven by these larger markets which can shift and, for any number of reasons, jeopardize their future availability. It therefore becomes important for the conservator to understand the relationship between polymer structure and some basic approaches to their assessment of key parameters so they can source a new material if necessary.

Polymeric structures typically have hundreds or more subgroups chemically bonded together with the same covalent bonds that hold the atoms within the subgroup together. For example, polyvinyl acetate can be illustrated as $(\text{CH}_2\text{-CHR})_n$, where R represents an acetate functional group attached to the vinyl group repeating n number of times. Polymer viscous and elastic (viscoelastic) properties manifest themselves at a molecular weight above approximately 10,000. The terms “polymer” and “resin” are sometimes used interchangeably, but resins, by contrast, are smaller molecules and have a molecular weight in the range of 500–1,000 (Horie 2010, 241–259).

Resins are sometimes referred to as oligomers (*oligo* meaning several). Like polymers, there are both natural and synthetic resins, but, in contrast, they are not as strong mechanically and may be tacky at room temperature. Waxes are a third class of materials of both synthetic (Horie 2010, 127) and natural (Mills and White 1994) origin, with an intermediate range of molecular weight. They are semicrystalline materials that have poor cohesive strength but function as matting agent additives in varnishes and control the heat set properties of heat-activated adhesive formulations. Some natural resins have a small polymeric fraction that researchers believe influences the handling properties of varnish surface coatings as solvent evaporates and the solute (solids) concentrate (de la Rie 1987). These two groupings—polymers and resins—offer a host of different intrinsic properties.

The structural protein collagen is a biopolymer-based glue with high molecular weight and strong cohesive strength. It has a long tradition of use in the assembly of wooden objects and remains an important conservation adhesive. Collagen glue is derived from helices of three intertwined polypeptides that when heated in water uncoil to form a highly viscous solution. Upon cooling it is impossible for the native helical structure to reform exactly as it was, and instead a three-dimensional network of smaller helical structures bridging more disordered phases is formed. These helical interconnections act as physical crosslinks that can be reversed in a heated aqueous solution. Collagen-based hide glues are characterized by two factors: open working time and strength. “Cold set”-type glues give the longest open working time, permitting the assembly of complex objects, and they have been discovered at archaeological sites along the Silk Road (Chamberlain et al. 2011). The strength of the glue is measured by its gel strength, a parameter related to weight in grams required to displace a plunger resting on a gel of fixed concentration under fixed conditions. Collagen-based glues remain water sensitive and subject to biodeterioration.

Starch, a plant-based polysaccharide responsible for energy storage, consists of a mixture of two biopolymers: amylose and amylopectin. Despite amylopectin having much higher molecular weight, its relative weakness is attributed to the polymers' randomly oriented (amorphous) structure. This amorphous structure also accounts for its solubility in cold water allowing for its separation from amylose. Generally, the strength of a starch paste adhesive depends upon the ratio of amylose to amylopectin and can be controlled by the source of the starch, as well as the extraction procedure for treating the starch granules. It is readily used in paper conservation because it is strong enough for most repairs and easily reversed; it can also be prepared in a variety of different ways. A weaker, less tacky starch-based adhesive is obtained when the starch is fermented: This material, common in Japan, is called furu-nori and thought to be flexible, though that claim has been disproven (Daniels 1988). Using a similar fermentation process, the polysaccharide adhesive from seaweed mucilage, called funori, can be made in a variety of ways. It can be used effectively as both an adhesive and consolidant for matt paint. Like collagen, polysaccharides are problematic for water-sensitive materials.

The structural polysaccharide cellulose has been a focus of early research in polymers before the structure of polymers was known. Cellulose, a plant-based high molecular weight biopolymer, is of little practical use as a conservation material (except in a supporting role as filter paper), but can be chemically modified to render it into a product soluble in solvents practical for conservation. The conversion to a potentially soluble material is achieved by a reduction in molecular weight and an increased functionality on the anhydroglucose unit via chemical industrial processing. A variety of industries use chemically modified cellulose esters (both organic and inorganic) for niche applications, while cellulose ethers are used as thickeners in many different markets. In conservation, cellulose ethers have been determined to weaken by virtue of chain scission degradation (Feller and Wilt 1990). However, they remain important materials effective for treating a variety of different media. Cellulose acetate and cellulose nitrate esters were at one time used in conservation and in particular

fieldwork where rapid drying is useful. However, both are known to degrade by discoloring and release acidic vapor. Water sensitivity needs to be evaluated for these classes of compounds on a case-by-case basis.

Synthetic polymers were quickly evaluated by practicing conservators as soon as their potential was fully elucidated and accepted by the scientific community in the mid to late 1920s. At Harvard's Fogg Museum, Gettens and Stout began testing synthetic polymers in 1929 as a consolidant for wall paintings and found them promising. Many different classes exist and some are formulated to be delivered as solutions, while others are specifically made for dispersions. The distinction is important: The viscosity of solutions is dependent upon molecular weight and concentration, while with dispersions, viscosity is primarily dependent upon thickeners in the aqueous phase often stabilized at a low pH. Polyvinyl acetates (PVAc), for example, exist as both solutions and dispersions (Horie 2010, 137–142). Dispersions have much higher molecular weight and produce durable films when dry—qualities ideal for many commercial paints and some, but not all, conservation applications. PVAc dispersions are difficult to resolubilize and typically only swell slightly and require mechanical removal, whereas solution-based PVAc acts as a viscoelastic solution. Solution-delivered PVAc comes in a variety of molecular weights, with the lowest most at risk of being too soft at room temperature. Oligomeric resins involving different chemistry, by contrast, are most easily removed because their lowest molecular weight of all makes them amenable to dissolving. They tend to have highly branched structures, which helps make them solid at room temperature. While most of the synthetic polymers and resins used in conservation are reversible in isolation, actual reversibility must be considered in the context of the treatment. This level of discrimination will narrow the field of the most suitable material for a given treatment.

Polymers can also include two monomers combined and fit the $(\text{CH}_2\text{-CAB})_x(\text{CH}_2\text{-CRS})_y$ description offering hybrid properties. Such materials are called copolymers. Some of the most commonly used conservation polymers are copolymers. Ethylene vinyl acetate (EVA) copolymers are important components to heat set adhesives used in conservation: The

waxy component of the polyethylene phase covalently linked to the polyvinyl acetate combines good melting properties with high cohesive strength (Ploeger, McGlinchey, and de la Rie 2016). Polyethyl methacrylate poly methacrylate (EMA-MA) copolymers are tough solids with solubility properties that tend to be acceptable for conservation applications. Polymers with three separate repeat groups are known as terpolymers; one example used in some areas of conservation is the so-called butyrls. These polymers contain vinyl acetate, vinyl alcohol, and vinyl butyral. They generally act as deep-penetrating consolidants for bone (Kres and Lovell 1995) and wood (Baker and Grattan 2011), though under extreme aging conditions they degrade and may cross-link (Horie 2010, 146).

All polymer systems described above dry by evaporation of some liquid—whether it is water or some organic solvent. Synthetic polymers fitting this description are considered thermoplastics, meaning they can be melted upon moderate heat treatment and solidified any number of times. That ideal is limited by oxidation or other chemical degradative processes.

Polymers that consist of long chains where any two distant atoms on the molecule can be traced via covalent linkages are classified as thermoset polymers. The entire mass can be visualized as a single molecule which will not liquefy with the application of heat but will eventually degrade at some elevated temperature. Such materials are insoluble regardless of the solvent once they are cured. However, like dispersions, some do swell slightly in specific solvents. This makes them unacceptable for many conservation applications, but there may be some instances where they are needed. Epoxies are examples of thermosetting materials that are sometimes used in conservation because they have excellent load-bearing properties. These systems may be suitable for certain nonporous surfaces, but epoxy cure is rather indiscriminant and will chemically cross-link to plant fibers and many polymers, making them inseparable and thus irreversible. When epoxies are needed for load-bearing applications, a thermoplastic barrier coating can at least prevent chemical bonding to the object, but remains technically difficult to reverse (Podany 2001).

SEE ALSO: Ethics in Conservation; Inpainting

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Preventive Conservation in Archaeological Sites

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Introduction

Preventive conservation is the act of preventing future loss and most definitions exclude actions that interfere with the structure and materials of the item. For archaeological sites, this definition is tested. Preventive conservation measures on finds and samples may primarily involve providing protective enclosures or preserving data, whereas preventive conservation for sites may involve installing temporary or permanent structures or making adaptations to context.

Preventive conservation in archaeological sites can be conceived of as the management of risks. Risk management aims to minimize negative consequences such as uncontrolled loss, while delivering maximum positive outcomes, such as preserving evidence or enabling access. Preventive conservation in archaeological sites should be part of the normal planning process and should be considered from the planning phase forward. This differs from conservation which intervenes in finds or features to uncover additional data or to extend the use of the material, such as micro-excavation of pots, the removal of corrosion, or the consolidation of structures (see CONSERVATION).

Preventive planning

Preventive conservation is a cyclical process. Key actions should be carried out before, during, and after excavation. Each stage should be reviewed and adapted as projects progress. Early planning facilitates the timely inclusion of preventive measures—for example, risk management,

monitoring, protective shelters, creating buffer zones, documentation, emergency preparedness, and visitor management. A multidisciplinary approach allows for the effective implementation of preventive measures, including prioritization of activities and funding. Initial activities are the creation of significance statements and identification of risks to the site and artifacts, leading to risk management strategies that can be integrated into the site management plan. Planning should include a review of relevant local and international legislation, standards, and charters. For sites revealing tangible structures, a conservation management plan should be developed, setting out strategies and resources for the long-term care and use of the archaeological site.

Significance assessment

Significance assessment for finds or samples may be as simple as establishing the research aims of the site and understanding how the sample contributes to them. Alternatively, this may be a complex process of understanding the nature of the site and associated beliefs. For excavators working outside of their own cultural expertise, this process will require significant effort to consider values in terms and formats that may be unfamiliar. Identifying stakeholders such as cultural representatives, land users, community leaders, and other interested parties may be necessary. It is possible for archaeological sites to have multiple and contested associations, posing challenges for preventive conservation strategies. A western scientific perspective may encourage a presumption that tangible material aspects of a site take predominance, but this cultural bias should be scrutinized to consider preserving patterns of ongoing use and interaction. It could reasonably be argued that removing an item from site represents a loss in intangible value, whereas leaving it in situ may threaten tangible aspects. Therefore, the implications of significance assessment should be addressed and revisited throughout the excavation and management of

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an archaeological site, to achieve balanced and informed preventive conservation practice.

Risk management

Preventive conservation strategies for archaeological sites require a risk awareness (see *DETERIORATION*) exercise to identify threats to both moveable and immovable features, followed by an assessment of their likelihood and impact, leading to a prioritized action list for risk mitigation. In considering the threats, the tangible and intangible values of the site must be assessed to ensure that both the material substance and the associated values are afforded protection compatible with future use (Paolini et al. 2012). In delivering preventive conservation strategies, a number of risks may be mitigated by the same remedial action; for example, a simple shelter may protect from rain, water, and sunlight.

In order to manage preventive conservation resources, it is necessary to collect data regarding the scale, impact, and likelihood of threats. For some risks this will involve the collection of environmental monitoring data on agents of deterioration, such as relative humidity and temperature. For other risks this will involve factors such as sociopolitical threat or an assessment of geological features.

Preventive conservation by documentation

In some cases, preventive conservation will aim to preserve evidence through documentation (see *CONSERVATION DOCUMENTATION*), from simple analog techniques of listing through photography, to advanced digital methods. Qualitative and quantitative documentation strategies can identify issues such as accelerated rates of deterioration or the efficacy of previous conservation interventions. Recording tools such as photogrammetry, terrestrial laser scanning, and augmented reality are useful in recording the archaeological process or in monitoring the deterioration of the in-situ archaeology. With recent politically motivated destruction, virtual reconstruction has been offered as a solution,

such as the virtual reconstruction of the Bamiyan Buddhas in Afghanistan. Crowd-sourcing techniques can contribute to data monitoring or recovering evidence of lost archaeological sites.

Changes in the depositional environment

Once exposed by excavation, archaeological materials undergo a rapid process of deterioration (Pedeli, Pulga, and Risser 2013). The archaeology that remains to be discovered has reached near equilibrium with its surroundings, slowing the rate of deterioration sufficiently to preserve evidence of its original form, albeit altered by the decay. Survival of archaeological evidence will be dependent on the chemical and physical nature of the material and the micro- and macroenvironment in which it is buried (Leuzinger, Sidell, and Williams 2016).

Preventive conservation efforts recognize the role of burial environment in the endurance of materials, and conservators implement measures to either recreate depositional conditions (e.g., by keeping wet organics wet) or compensate for them by conservation intervention. Inorganic materials such as stone and ceramic tend to survive best. The preservation of glass and metal will depend on the burial environment, with stable conditions slowing rates of decay, and sudden changes in microenvironments accelerating decay. The amount of oxygen available in an environment (aerobic or anaerobic) can indicate the scope for organic preservation and the scale of microbial and fungal degradation (Corfield 1996). Extreme conditions such as low oxygen or temperature favor the survival of organic materials and reduce rates of chemical decay such as corrosion. Those extremes are found in environments such as peat bogs (anoxic), ice (low temperature and humidity), or desert (desiccation). For sites in enclosed spaces with a delicate microbial balance, it is important to monitor for changes both during and after excavation.

Environmental monitoring

Preventive conservation at archaeological sites, in particular those with microclimates or extreme

conditions, requires the collection of data on agents of deterioration such as humidity, temperature, or pollution. Fluctuations in climate can contribute to deterioration on both annual and diurnal scales. Sites that experience broad climatic shifts are at risk of damage due to freeze–thaw cycles, whereby mechanical damage is caused in winter or at night. Sites that are enclosed (e.g., caves/tombs/shelters) may limit some agents of deterioration such as light and wind, but are more at risk from the development of condensation (dew point). The introduction of people to a site, changing patterns of use, or the uncovering or removal of features such as stones within a tomb entrance will change environmental conditions and disrupt equilibrium. Ideally, a preventive conservation strategy will collect baseline environmental data preceding any intervention.

Problems arise where soluble salts and other contaminants are present as they react with changes in the environment, leading to deterioration and mechanical stress. Soluble salts deliquesce and crystallize with fluctuations in relative humidity, leading to efflorescence, sub-fluorescence, and cryptofluorescence in porous materials. Repeating cycles of salt crystallization leads to both surface loss and structural failure of contaminated substrates. While some small finds can be treated for salt contamination, salt present within in-situ features can only be mitigated with environmental controls.

Pollution in urban sites can both accelerate deterioration and create aesthetic damage. Changes in land use and climate change may lead to changing trends in environmental conditions, such as the drying of subsoil, more frequent heavy precipitation events, or rising temperatures. These can lead to both minor changes such as mold growth and major ones such as ground movement or the development of fissures. Some data may be available locally: many national and regional agencies collect data such as temperature, humidity, precipitation, and pollution. Where the site is remote, in a country with limited resources, or contains a microclimate, independent monitoring may be required. Equipment to monitor and transmit data has evolved rapidly, allowing the opportunity for remote logging of sites.

Geology and landscape

Monitoring the hydraulic behavior of the depositional environment is an important part of developing successful preventive conservation practice and acts as an early warning of destabilization (Corfield 1996). Changes in patterns of water movement such as diverting or damming rivers can affect the geology for a large area. Sudden changes in conditions such as a shifting water table may generate significant preventive conservation challenges in a cave or *tell* (artificial mound), many miles away. Successful in-situ preservation depends on a critical understanding of how different factors interrelate (Corfield 1996). Good data monitoring will alert site managers to changing conditions that may lead to investigations of changes in land management patterns in the region.

Shelters

Coverings and shelters can be useful tools for preventive conservation. Textiles such as geotextiles, Gortex, Sympatex, and agricultural netting can be useful in aiding stabilization. Shelters provide a barrier to reduce the impact of inclement weather; protection of delicate features and archaeological sections; reduction of light and ultraviolet damage; cover for ongoing excavation work; and can restrict access or theft and be a beneficial alternative to backfilling (Pedeli et al. 2013). Developing a shelter can be a difficult and expensive endeavor and requires planning, taking into account the climate (both in and outside of the structure); plans for future excavation; the physical impact to the existing archaeology and landscape; and maintenance. If built incorrectly, a permanent shelter can lead to the creation of undesirable microclimates, condensation, and water channeling, and impede study and photography, or collapse on to the archaeological substrate. The installation of shelters may itself be damaging to the context. The impact of any shelter should be considered as part of the conservation management plan for the site.

Emergency preparedness

A plan for disaster mitigation and preparedness requires a comprehensive assessment of catastrophic risks to site, occupants, and visitors. Catastrophic events include sudden ecological or geological events, climate change, and severe weather events, illegal activities, and deliberate destruction. Disaster risk reduction strategies should involve local community members and relevant stakeholders, and include awareness-raising and procedural training. Measures should be put into place to facilitate rescue and response.

Site management

Where a site is frequently accessed, visitors can negatively affect the environment, damaging evidence by benign or deliberate means. Site management might recognize the erosion of an earthen feature by walkers, or wear marks caused by patterns of touching or use. These impacts can be managed by the careful manipulation of the environment through landscape features, the creation of alternative routes, strengthening of walk areas, and access restrictions such as the recent changes to Stonehenge. Deliberate damage such as carving of initials, graffiti, or theft will generally require different preventive conservation strategies. Deliberate damage to a site may also occur due to a lack of awareness of the site's significance, a desire to plunder local resources, or a resentment of public use of an area, such as the Noh Mul Maya pyramid in Belize. In these cases, preventive conservation measures may be structural (fences and locked

gates), social (a campaign of local public engagement and support for site management), or legal (the legalization of protection with associated enforced penalty system for damage). UNESCO's World Heritage Site status can be seen as a preventive conservation measure in this context.

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Raman Spectroscopy in Conservation

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Raman spectroscopy is now a fundamental analytical technique in art conservation, in archaeometry, and, in general, in the study of heritage material. Coupled with microscope optics, a Raman spectrometer makes it possible to characterize with high spatial resolution and in a nondestructive way a range of materials such as pigments, dyes, minerals, gems, glass, ceramic glazes, and synthetic polymers. The technique is often used as part of an analytical chain that includes X-ray fluorescence (XRF) spectroscopy, Fourier transform infrared (FTIR) spectroscopy, and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS). Compared to XRF, which offers only elemental composition information, Raman, a vibrational spectroscopy technique, easily discriminates polymorphs (for instance, anatase and rutile, two forms of the common white pigment titanium dioxide). Compared to FTIR, another vibrational spectroscopy technique, Raman yields different yet complementary information, because of the difference in selection rules for Raman scattering and infrared absorption and for the radically different experimental setup.

The Raman effect, discovered in 1928 by Indian physicist C. V. Raman (who was awarded the Nobel Prize in Physics in 1930 for the discovery), is an inelastic light scattering effect whereby an extremely small fraction of the photons impinging on a sample is scattered with a defined energy loss (or gain): This is commonly called the Raman shift. The energy difference between exciting and scattered radiation corresponds to the energy of a vibrational transition for the substance analyzed. Complex molecules may show an array of shifts, corresponding to all the possible vibrations of the different bonds in the molecule: This is the Raman spectrum.

In practice, when investigating a material by Raman spectroscopy, an extremely bright source such as a laser is focused on the sample with appropriate optics and the backscattered radiation is collected (usually with the same optics, in a 180° geometry), filtered to block the exciting radiation, dispersed into a range of frequencies, and projected onto a high-sensitivity detector (in modern practice a silicon charge-coupled device (CCD)). The resulting intensity versus the Raman shift graph is the Raman spectrum of the material. Raman spectroscopy is a vibrational spectroscopy technique: It is sensitive to the arrangement of atoms in a molecule and to the way molecular bonds vibrate (stretching or bending) when the molecule is excited. Compared to infrared absorption spectroscopy, where vibrational levels are probed directly by measuring the absorption of infrared light by the sample, Raman spectroscopy differs for the basic nature of the phenomenon. Raman scattering occurs when the polarizability of a chemical bond (the ability of the molecule to acquire an instant dipole moment or separation of charges under the influence of an external electromagnetic field) changes between two vibrational states (in the case of bond stretching, for instance, when the molecule is more easily polarized in the excited (stretched) state than in the relaxed state). Infrared absorption occurs when the permanent dipole of a molecule changes as a result of a vibrational transition. These two complementary sets of conditions, called selection rules, define the different molecular characteristics that are highlighted by each experiment. Infrared spectroscopy is more sensitive to the vibration of highly polarized chemical bonds (for instance, the carbonyl bond in organic acids and esters) and Raman spectroscopy is more sensitive to chemical bonds with lower polarization (such as the carbon-carbon bonds in the chain of an organic polymer). The two techniques differ also in how they are carried out experimentally. In FTIR, infrared light in the 2- to 20- μm wavelength range is used, while in Raman spectroscopy, visible or near-infrared light is generally used (488–785 nm, with some instrumentation using also 1064-nm excitation).

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The use of visible light makes it possible to couple Raman spectrometers to optical microscopes, achieving great spatial resolution.

Raman spectroscopy was first applied to the analysis of heritage materials in the 1980s (Guineau 1984), yet it is the work of Robin Clark at University College London that definitely established Raman as a valuable technique in art conservation and archaeometry (Bell, Clark, and Gibbs 1997). A typical application of Raman spectroscopy highlighting its key advantages over other analytical techniques is shown in Figure 1.

The large free-blown glass paten is decorated on the underside in a technique called reverse painting. The paint is applied directly to the underside of the glass bowl, starting with the highlights, followed by the paint and metal foils for the figures and the background, and finally the ground layer. Everything is then covered with an opaque wax layer. The pigments are essentially inaccessible for sampling or for non-destructive analysis by techniques such as XRF, sandwiched as they are between the thick (5–7 mm) glass and the opaque wax coating. With an open-architecture Raman microscope equipped with long working distance objectives, it is possible to focus the laser beam through the glass onto

the paint layer and identify the pigments used by the artist. Similar work has been done on portrait miniatures such as Nicholas Hilliard's *Armada Jewel* (Derbyshire and Withnall 1999). Excellent reviews are available describing in great detail the application of Raman spectroscopy to the analysis of heritage material, including paintings and drawings (Centeno 2016), and archaeological artifacts (Bersani and Lottici 2016). In addition to pigments and minerals, materials of interest in conservation and archaeometry that have been successfully investigated by Raman spectroscopy include synthetic pigments (Ropret, Centeno, and Bukovic 2008) and copper corrosion products (Trentelman et al. 1999).

The key limitations of Raman spectroscopy are low sensitivity, a consequence of the relative weakness of the Raman effect, and interference from luminescence. The latter is of particular importance, as many substances of interest in heritage studies can fluoresce under laser excitation: These include not just impurities or degradation products that may be commixed with the analyte of interest, but in some cases, as for natural and synthetic organic colorants, the analytes themselves.

A possible strategy to reduce the interference from fluorescence is to employ long wavelength

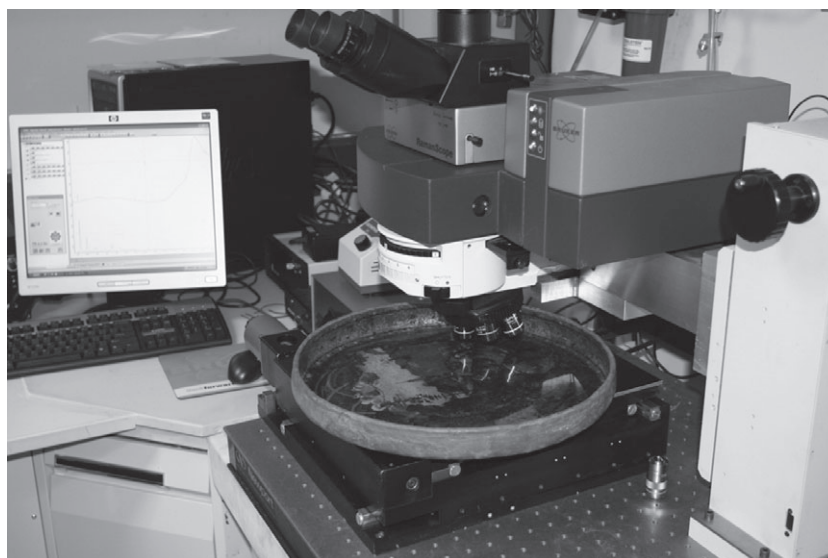


Figure 1 Dish with Abraham and Melchizedek, 1498 (Hans of Landshut, German, Landshut, active late fifteenth century). Overall dimensions: 36.9×4.2 cm.

Source: The Metropolitan Museum of Art, The Cloisters Collection, Accession Number: 2008.278.

excitation radiation. This is accomplished with near-infrared lasers, typically at 785, 830, and 1064 nm. The first wavelength is the one that is most commonly found on microscope-coupled dispersive Raman spectrometers. It offers significant reduction in fluorescence compared with blue or green wavelengths, but it cannot completely eliminate the fluorescence typical of organic colorants. More recently, 830-nm lasers have become available, and are being incorporated into portable Raman systems. Finally, 1064-nm lasers offer the best performance in terms of reduction or avoidance of fluorescence interference. This excitation wavelength, however, requires substantially different hardware: either interferometer-based spectrometers with germanium diode detectors (Fourier transform Raman spectroscopy) or dispersive spectrometers with indium gallium arsenide (InGaAs) detectors. A spectral library of pigments investigated by Fourier transform Raman has been published by Burgio and Clark (2001).

More recently, an alternative approach to investigate highly fluorescent materials, surface-enhanced Raman spectroscopy (SERS), has found considerable application in art historical, archaeological, and art conservation studies, particularly for the identification of organic colorants. In brief, organic molecules adsorbed on the surface of atomically rough metals such as gold, silver, and copper experience an extremely high increase in their Raman scattering intensity. Surface-enhancement of Raman scattering is caused by a combination of local electromagnetic field enhancement at the surface of a nanoparticle (or, better, at the junction of two or more nanoparticles) and charge-transfer resonance between a metal nanoparticle and adsorbed molecule. The effect has been more properly described as surface-enhanced Raman resonance scattering (SERRS) to highlight both factors. In practice, a molecule adsorbed on the surface of a metallic nanoparticle experiences under laser excitation a much larger electromagnetic field and it may be closer to resonance Raman conditions than in the absence of the metal nanoparticle.

SERS is carried out by adding metal nanoparticles, typically a silver colloid to a sample obtained from the object under examination. As the organic colorant diffuses out of the sample and adsorbs onto the surface of the nanoparticles, its

SERS spectrum can be recorded. While SERS is not a nondestructive technique, the extremely high sensitivity of the method makes it possible to obtain excellent spectra from samples as small as 20 μm in diameter. Recently, alternative approaches to SERS based on the use of silver nanoparticles dispersed in gels to produce the SERS effect directly on the object under examination, without removing a sample, have been tested. Similarly, the use of inkjet print-heads to deliver picoliter droplets of silver colloid to a print or drawing, thus leaving only microscopic residues on the object, has been proposed. Finally, coupling laser ablation to SERS has been shown to increase the sensitivity of the method for the analysis of painting cross-sections, while at the same time achieving spatial resolution in the order of 5–10 μm .

Typical material investigated by SERS include dyed textile fibers, dyed feathers, lake pigments from archaeological objects, drawings, prints, watercolors, paintings, and polychrome objects. All natural dyes of artistic and archaeological interest (such as madder, kermes, cochineal, lac dye, brazilwood, logwood, orchil, weld, fustic, berberin, and safflower) and a number of synthetic dyes (among them magenta, methyl and crystal violet, eosine, erythrosine, safranin, and mauveine) have been characterized by SERS. A comprehensive review of SERS applications in art and archaeology has been published recently (Pozzi and Leona 2016).

SEE ALSO: Archaeometry; Chemistry in Archaeology; Conservation Science; Dyes; Gemstones; Glazes, Slips, and Paints; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Ink; Pigment Alteration; Raman Spectroscopy; Raman Spectroscopy and Material Analysis; X-Ray Fluorescence Spectrometry (XRF)

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Reflectance Transformation Imaging (RTI) in Conservation

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The RTI technique and variations common in conservation applications

Reflectance transformation imaging (RTI) is a computational photographic method widely used in the conservation laboratories of heritage institutions worldwide. The basic concept of this technique is that, instead of capturing and viewing a single image of an object, the conservator captures a sequence of images of the object. Using computer algorithms, data can be extracted from that sequence of digital images and used to synthesize a new digital representation or type of image. This new image reveals surface information not visible under direct empirical examination of the subject and not visible in any of the original individual images. RTI is based on the polynomial texture mapping (PTM) technique that was first developed at Hewlett Packard Labs (Malzbender, Gelb, and Wolters 2001). Subsequent research has greatly extended heritage applications and led to the development of alternative algorithms for data extraction, including the widely used hemispherical harmonics (HSR) approach (Mudge et al. 2008). The nonprofit organization Cultural Heritage Imaging (CHI) has taken a leading role in research and education in this technique, with extensive outreach to conservation professionals in the United States. CHI provides freely available software and online resources such as a capture guide and instructional videos, as well as equipment kits and periodic workshops, thus enabling conservators to access the technique (<http://culturalheritageimaging.org>).

Most conservators now use the highlight RTI image capture method. In this technique,

multiple images (often 48 or more) are taken with the subject in a fixed position and the camera remaining stationary on a tripod, while the light source is moved from point to point in the shape of a dome around the subject, always maintaining a constant (measured) distance from the subject (Cosentino 2013). Ambient light is excluded as much as possible, so that the light comes primarily from the strategically placed light positions. Each image in the series will have varying highlights and shadows. One or more black reflective spheres are photographed alongside the subject, reflecting back a lit highlight that the software uses to determine the exact location of the light source for each image in the series. The software needs the known light positions to calculate the “surface normal” of each pixel (i.e., the vector perpendicular to the point where the light touches the surface); these surface normals provide information about 3D morphology of the surface. Since each surface normal connects to a point on the object, the entire series indicates the topography. An alternative to the highlight method is to use a purpose-built dome with a light array permanently installed. This is an efficient system for large throughputs with relatively small subjects, but building such a light array can be expensive. In contrast, the highlight RTI method is low-cost enough to be accessible to even small conservation laboratories, private conservators, or archaeological field conservation laboratories.

The RTI Builder software processes the images (<http://culturalheritageimaging.org/>) using the illumination information gathered from the entire suite of images to generate a mathematical model of the object surface. The software synthesizes the entire image series into a single RTI 2D image that carries 3D information through the combination of shadows and highlights and the surface normal data. The software can calculate this 3D information because the positions of the subject and camera remain fixed, many different light positions are used, and the exact position of the light source can be determined for each image in the series. Two mathematical methods for extracting surface normals are available: the older

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polynomial texture map (PTM); and the newer hemispherical harmonics (HSH) approach. Recent research shows that the latter produces improved 3D rendering (Manfredi et al. 2014).

The RTI Viewer software (<http://culturalheritageimaging.org/>) enables interactive relighting of the subject from any direction and under a variety of filters that improve the contrast between surface details and enhance surface texture. For example, it is possible to remove the color data so surface morphology is the focus. Mathematical enhancement of those morphological features may reveal new information. The surface can be rendered shiny (specular), so that fine surface details are more visible. Conservators can extend the power of RTI even further by combining the technique with infrared or ultraviolet light, or by using it under a microscope.

Qualitative RTI in conservation

The ability to increase the amount of surface information visible is a clear advantage for many conservation tasks. Standard photographic techniques often do not adequately document all the details of the surface texture of an object. The enhanced surface detail available with RTI can often allow conservators to discern evidence of fabrication or manufacturing methods that can help identify an artist or a period, place, or technique of production (see Figure 1).

For example, Artal-Isbrand and Klausmeyer (2013) used RTI to answer questions regarding tools, craft techniques, and production sequences used by Greek red-figure vase painters. Topographical features of painted ceramics, such as preliminary sketch lines, broad contour lines surrounding figures, and relief lines used to outline figures and to indicate shapes such as ears and eyes, were more clearly discernible with RTI than with other photographic techniques. The RTI examination also provided insights into the production sequence used by the painters, by revealing the order in which each step was executed.

The enhanced surface details produced through RTI also enable conservators to conduct more thorough condition assessments, provide stronger condition documentation, and analyze better the effects of conservation treatments (see Figure 2). For example, experiments show that

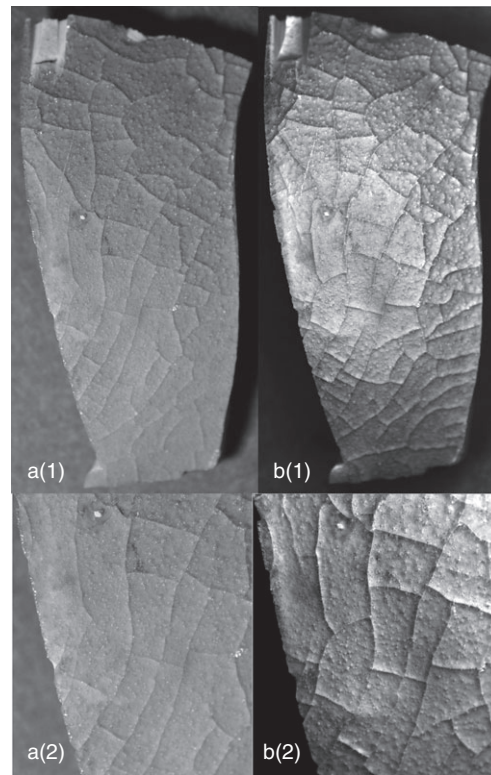


Figure 1 Song dynasty green-glazed shard from Sichuan Province, China: shown in raking light (a) by comparison with RTI specular enhancement (b), both with overall view (1) and a close-up view (2). The crack patterns in the glaze are an important technical feature in Chinese ceramics, and these details are more clearly visible in the RTI images. Bubbles in Chinese glazes are often deliberately engineered for optical effects; the many small bubbles here are better defined in the RTI image, which also highlights the presence of small, round, dark spots of concentrated iron oxide colorant.

Source: Author.

RTI is an important aid in the conservation condition assessment and documentation of ancient coins (Kotoula and Kyranoudi 2013). It was found to be very helpful in coin identification, even for very low relief details and for highly corroded coins. It also improved conservation examination and condition-reporting steps by enhancing surface effects such as pitting, scratches, corrosion, surface deposits, and areas

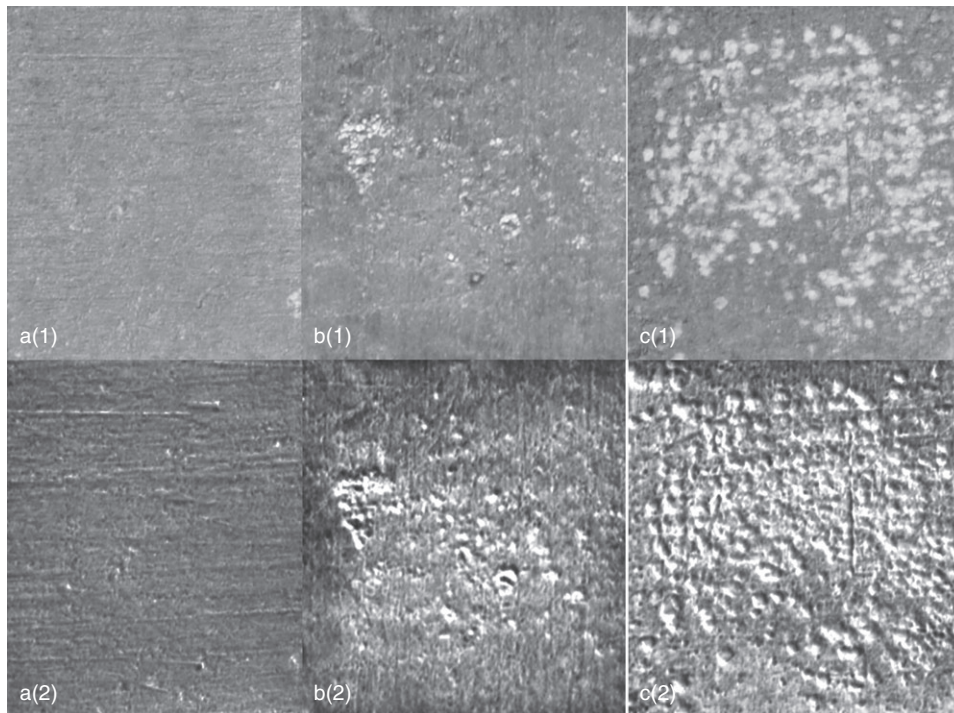


Figure 2 Three lead coupons were artificially aged under exposure to different exhibition and storage materials, each causing differing amounts of corrosion: (a) has essentially no corrosion, and the parallel lines of polishing marks are visible; (b) has some corrosion, obscuring some of the polishing lines; and (c) has severe corrosion and almost no polishing lines remain. Each coupon is shown in raking light (1) by comparison with RTI surface enhancement (2). While the raking light views show some of the corrosion products, these are more visible in the RTI images, as is the surface texture of polishing lines and pitting corrosion.

Source: Author.

of loss, so these could be more fully described and documented. The surface effects of conservation treatments could also be better visualized and monitored.

RTI successfully identified textural features not visible to the eye or through raking light photography on a seventeenth-century watercolor landscape painting on paper support (Manrique Tamayo, Valcarcel Andres, and Osca Pons 2013). These textural features included previously unknown details about the artist's working method. RTI showed that the artist used a hard tool such as a pencil or ink pen to delineate the outlines of buildings and roads. This technique left subtle impressions on the paper that became visible only through RTI. Other textural features related to the preservation condition of the

watercolor were also enhanced by RTI, including wrinkling and other deformations of the paper, joins, and fold marks. In another paper example discussed by the same authors, a colored print from a seventeenth-century book, RTI indicated that that artist had used two different pieces of paper to create a single page. The evidence was that laid lines on the main illustration became visible with RTI, but the rest of the page was lacking those laid lines.

RTI has also been successfully used in paintings conservation. For example, it was applied to the condition assessment of a sixteenth-century oil painting on a wooden support panel (Manrique Tamayo, Valcarcel Andres, and Osca Pons 2013). RTI was helpful in discerning a wide variety of condition

characteristics such as deformation of the wood panel, cracking of paint layers, scratches, areas of paint loss, and cupping. RTI also helped the conservators identify texture or brightness discontinuities that marked the places where repainting or previous cleaning had occurred. The same authors applied RTI to another sixteenth-century oil painting on a wooden panel support in order to monitor and evaluate the success of a conservation treatment. In this case, the painting had endured a fire during the Spanish Civil War of 1936, and this event had resulted in many blisters on the paint surface. The large blisters could be documented through raking light photography, but the small ones (less than 1 mm diameter) could not. RTI was successful at revealing and documenting these very tiny blisters. Monitoring the success of the treatment for consolidating and flattening blisters continued with RTI incorporated into the workflow.

Architectural conservators are now using RTI in an outdoor environment, although adjustments to the capture technique are necessary when one is working outdoors rather than in a dark studio. For example, Gabov and Bevan (2011) demonstrated the utility of RTI in the examination and treatment of weathered sandstone and limestone façades. RTI documented better than standard photographic methods the evidence for production methods, such as original tool marks, and for deterioration features, such as surface spalling. The specular enhancement feature of RTI showed much better than natural-light photography the extent of surface spalling. In the case of Gabov and Bevan's façades, RTI revealed that little of the original surface remains intact. Yet in spite of the surface deterioration, RTI indicated the presence of original letters carved onto the surface of the stone. The details of the photographic setup were meticulously recorded (e.g., the distance of the camera from the object photographed, the height of the camera from the ground, and the dimensions of the object), and the camera was perfectly aligned, either on a vertical or on a horizontal plane. As a result, the RTI process should be repeatable under similar conditions in the future, which is important for conservation documentation and continued condition monitoring. Gabov and Bevan concluded that the improved documentation ability, coupled with the ease of

use and the low cost of the RTI technique, meant that this should be seen as a standard part of the tool kit for recording architectural stone surfaces before and after conservation treatment.

Many conservation research groups are also carrying out ongoing experiments designed to incorporate RTI into other examination and documentation workflows typically found in a conservation laboratory. For example, incorporating infrared photography and ultraviolet photography with RTI extends the capabilities of the technique. It is also possible to incorporate RTI into optical microscopy examination, for microscopic RTI. Kotoula (2015) combined RTI with multispectral imaging, capturing highlight RTI images with a UV-VIS-IR camera, a range of filters, and IR or UV radiation sources. She applied this technique to the study of glazed ceramics and found that this approach provides much information about production methods, condition, and conservation treatment effects. For example, this extended RTI approach revealed evidence of pressure applied by the potter at joins, preparatory drawings under glazes, and the sequence of color applications. The extended RTI also indicated the initiation of salt efflorescence, scratches, areas of missing glaze, microcracks, and tiny blisters in the glaze; and it enhanced the topography of any surface damage or glaze deterioration. It also clarified the presence and morphology of past repairs. Remains of materials that had been applied in past conservation treatment campaigns could be discerned, both on the surface and within repair areas.

Quantitative RTI in conservation

RTI also shows promise beyond interactive relighting of an object from any light direction and the resulting qualitative surface enhancements. The ability to document surface texture in a quantitative manner is crucial for a conservator who needs to analyze changes that occur over time. Examples are the subtle or progressive changes due to inadequate environmental conditions that may be causing deterioration of the object; or changes seen before and after the application of a conservation treatment, whether these are intended goals of the treatment or inadvertent

and unwanted side effects. Quantitative work always requires that the conservator take care to ensure that there is a fully measured, recorded, and repeatable photographic setup. Quantitative RTI has found use in the condition documentation of objects, in measuring and monitoring deterioration, and in assessing the results of conservation treatments. It is also being used in the development and testing of the visual effects of new conservation materials (such as adhesives, protective coatings, cleaning materials and methods, etc.). RTI can help ensure that the proposed new materials or treatment techniques will not negatively impact the appearance of the surface of an object. While quantitative RTI is still a relatively new and emerging technology, useful applications of it have been reported in the conservation of paper, paintings, a variety of museum object types (ceramics, stone, metals, wood, bone, and leather), and outdoor architectural stone.

For example, Manfredi et al. (2014) carried out experiments using a model drawing that they created in order to examine how reproducible and quantifiable RTI can be for measuring surface changes. By monitoring the surface normals over time, it is possible to detect small-scale morphological and physical changes in an object that may be due to exposure to the environment or to a conservation treatment intervention. However, a surface normal for a particular pixel can only be considered changed by the environment (or conservation treatment) if the value exceeds a statistical control (the accidental variation encountered from one RTI session to another). Manfred and colleagues measured the repeatability of computed surface normals by recording all of the image sequences for RTI five times, in five separate imaging sessions. They moved the camera position slightly for each session (to mimic setting up separate photography sessions at different times). They computed the surface normals from these image capture replicate sessions using both the PTM and the HSH methods. The average variability was then calculated. The authors found that, while the PTM method is not repeatable, the HSH method is in fact very reproducible and therefore more sensitive to detecting actual surface changes than is the PTM method.

Manfred et al. (2014) subsequently developed an RTI monitoring protocol using the HSH

method that successfully detected damage they deliberately made to their experimental drawing. They considered change to have occurred only in those pixels that were offset to a greater degree than the statistical limit of variability. They created a map of the changed pixels, to illustrate the changes that occurred to the damaged model drawing. This work demonstrates that RTI can be reproducible and quantifiable enough to be used as a practical method for measuring change over time on the surfaces of cultural heritage objects. Research into improving the accuracy of quantitative RTI is still being made by various groups. This work includes efforts to incorporate the most accurate surface normal calculations possible into the available open-source RTI software tools.

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Terahertz Imaging in Conservation

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Electromagnetic waves are widely used in heritage science in nondestructive testing methods. The penetration depth and spatial resolution depend on the frequency and the test object's physical properties. For example, X-ray radiography reveals the internal structure of an object if it can be placed in the system. X-ray fluorescence (XRF) and ultraviolet and infrared waves are used for material analyses, as well as spectroscopic imaging. In archaeology, microwave radars or ground-penetrating radars (GPR) are also commonly used to investigate objects under the soil. The frequency range between microwaves and infrared (i.e., terahertz or THz waves) is one of the emerging technologies in heritage science. There are several commercially available THz imaging systems that are transportable, and there have been various experimental studies demonstrating the advantages of this frequency range (Jackson et al. 2011).

The frequency of terahertz waves is typically between 0.1 and 10 THz (1 THz = 300 μm , 33.3 cm^{-1} = 4.2 meV, 48 K). In addition to classical THz spectroscopy using a Michelson interferometer (i.e., the far-infrared option of a common FTIR spectrometer), THz time domain spectroscopy (TDS) technology was developed in the 1990s. A THz-TDS system uses a narrow pulse, the width of which is of the order of picoseconds. By applying a fast Fourier transform (FFT) to the transmission pulse in the time domain, spectra in the frequency domain are obtained. Since the energy of THz waves corresponds to weak bonds, THz spectroscopy is expected to be an analysis tool for organic–inorganic composites, including paints. In fact, there was active research on mineral pigments in the 1960s and 1970s during the development of FTIR spectroscopy (Karr and

Kovach 1969). Early attempts to apply THz technology to artworks were aimed at spectroscopic imaging. Although model experiments suggest the possibility of material analyses, reflection signals from real artworks are not sufficiently clear to identify a given substance. Thus, other established methods, such as XRF or IR, are used to clarify experimental data. Since these analytical techniques often require sampling or observing a small area at a given time, it is practically difficult to obtain an entire material map of an artwork. On the other hand, THz imaging can roughly indicate the material distribution in shorter time than XRF, meaning that a THz reflection image can suggest points where precise measurements should be made. For example, a fragment from a wall painting at the Dazhao Monastery in Inner Mongolia, which was previously analyzed by XRF and Raman spectroscopy, was analyzed by THz imaging (Fukunaga et al. 2010). The XRF and Raman spectroscopy data were obtained from points chosen by a researcher's visual inspection. Lead was detected from one point in an orange area; and the orange color in this fragment was determined as minium at that time. The reflectivity of THz waves in this orange area was found to be high. However, THz imaging revealed that there are some orange parts that show low reflectivity. This result suggests that another orange material was also used. Therefore, XRF element mapping was performed to investigate this aspect of the orange color. The orange parts that have high reflectivity in the THz image were painted with a lead-based pigment, which is most likely minium. On the other hand, no specific mineral was found for the orange parts with low reflectivity. As illustrated by this example, THz imaging is a complementary technique for indicating points to be measured by using other well-established measurement methods.

In this decade, many research groups around the world have been actively using THz imaging techniques. Experimental results obtained with different types of objects, such as panel paintings, wall paintings, and archaeological vases, have proved that the THz frequency band

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has particular advantages in internal structure observation using a THz pulse. Noninvasive cross-section images at the positions of interest and area images at the depths of interest are the biggest benefits. One practical advantage of THz imaging is the ability to detect separation in a multilayered object, because a layer of air between two dielectric materials produces high contrast in the imaging results. Separations occur between supporting materials (e.g., paper, wood, canvas, stone, brick) and preparation layers (e.g., mortar, gesso, clay), or between preparation layers and painting layers. Even if a visible crack on the surface is thin, the separation area underneath could be large. By using THz imaging, conservators can see internal defects and can choose an appropriate technique. In the case of Japanese panel screens made of multilayered pieces of paper, the entire internal structure, such as a glued area or the condition of a calcite preparation layer, can be visualized precisely. Structural information on these light materials is not easily obtained by X-ray radiography in transmission mode. Thanks to the strong reflection from a metal surface, THz imaging can easily detect metallic objects, such as gold leaf, under dielectric materials. For THz experts, this may be too simple to be recognized as an important application of the THz imaging technique. However, it is practically useful for conservators, because a painted area with gold leaf underneath is extremely fragile.

A THz area image is generally obtained by TDS by integrating the reflection pulse sequence at each point during the scanning. An area image can be formed by assigning values at each measurement point, for example, the maximum value as white and the minimum value as black. By extracting a specific reflection pulse in the observation area, the condition of the layer of interest, such as the surface of a supporting material, can be examined. Thus THz imaging can be used to analyze a painting as if it has been sliced layer by layer from the surface. Some studies have revealed the condition of a wood surface and the internal defects of panel paintings (Fukunaga and Picollo 2010). In addition to THz-TDS imaging, there are also imaging systems that use continuous waves (CWs), including THz tomography systems, and quasi-real-time imaging systems developed with resonant-tunneling diodes (RTDs) (Miyamoto et al. 2016). Bordeaux University has developed

a THz CW tomography system (THz scanner) using a Gunn diode source operating at 110 GHz. The system has successfully examined the interior of sealed Egyptian vases and found objects inside, which could not be observed by X-ray radiography (Caumes et al. 2011).

The number of THz users in the heritage science field is increasing rapidly, and the first international conference dedicated to the application of THz technology to the examination of art objects was held in 2014—more than 70 people attended. By accumulating case studies and improving signal analyses, THz technology will provide more useful information for conservation science in heritage studies in the near future.

SEE ALSO: Imaging; Multispectral and Hyperspectral Imaging of Artworks; Radar; X-Ray Radiography; X-Ray Tomography

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Archaeointensity

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Direct measurement of the geomagnetic field intensity has only been available since 1833, when Gauss developed in 1832 an instrument for its measurement. Prior to that epoch, the estimation of past geomagnetic field strength requires the paleomagnetic analysis of rocks and baked archaeological material that carry a remanent magnetization of thermal origin, that is, a thermoremanence. Contrary to the directional geomagnetic elements (declination and inclination), for which measurement protocols in the paleomagnetic laboratories are well established, the archaeointensity determination is more complicated and requires very long experimental times. This is one of the reasons why recent archaeointensity compilations are poorly distributed, both temporally and spatially. Archaeointensity data are key for better understanding the past Earth's magnetic field, since this geomagnetic element is crucial for accurate dipole moment estimations (Valet et al. 2008), that are used to constrain geodynamo numerical models and to reconstruct the past solar activity based on geomagnetically dependent radionuclide records. In addition, the time variation of the past geomagnetic field intensity can potentially be used to date archaeological material or volcanic rocks by means of the archaeomagnetic dating method (see *ARCHAEOMAGNETIC DATING OF BAKED CLAY FEATURES*).

Physical background and archaeointensity measurements

The physical phenomenon behind the archaeointensity measurements is the same as that detailed

for archaeomagnetism (see *ARCHAEOMAGNETISM*). In short, some archaeological materials contain iron oxides, such as magnetite or hematite, that, after heating above the Curie temperature, have the ability to record the direction and strength of the ambient magnetic field present at the moment of cooling. This kind of magnetization is denoted as thermoremanent magnetization (TRM) and is preserved in the material until further heating. These iron oxides can be found in a wide range of archaeological structures (e.g., kilns, furnaces, ovens) because of the clay products used for their construction. Recent studies also suggest that materials from archaeometallurgical context (e.g., slag deposits) are suitable for archaeointensity estimations.

Although the first works on archaeointensity determination were published by Folgheraiter (1899) and Koenigsberger (1938), Thellier and Thellier (1941) were the first scientists to obtain reliable archaeointensity data from bricks and other baked clays. Their experiments were based on the proposal of Folgheraiter (1899) who established that the ratio between the past field intensity and the present field intensity is equal to the ratio between the natural remanent magnetization (NRM) produced by cooling in the past field and the TRM after cooling in the present field; in mathematical terms, $H_{\text{past}}/H_{\text{present}} = \text{NRM}/\text{TRM}$. According to the previous expression, a plot of NRM lost versus partial TRM (pTRM) gained, called the Arai plot, should give a straight line whose gradient is used to determine the archaeointensity data. The associated uncertainty can be determined from the fitting goodness of the slope (by a linear regression). Under this assumption, Thellier and Thellier developed a laboratory protocol, which consists in a double heating-cooling cycle performed in two opposite magnetic fields (Thellier and Thellier 1959). This method, together with the previous Néel's theory (Néel 1949) for the TRM of single domain grains, established the physical bases to understand how an archaeological heated material can be magnetized. As recognized in these works, two fundamental magnetic properties—the grain size of the magnetic

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particles and the shape of the minerals—play a major role in TRM acquisition. Nevertheless, these methods and laws are valid for ideal conditions, and many problems can occur when experiments are performed on natural assemblages containing a wide range of magnetic minerals and grain sizes (Dunlop 2011). The identification of these problems is a major scientific barrier that is challenging the paleomagnetic community at present.

The most common problems, which lead to unsuccessful intensity determinations, are thermally unstable ferromagnetic phases, the presence of coarse (multidomain) grains, and secondary remanent magnetizations. In order to detect these common problems and to check the ability of the specimens to reliably record the ancient geomagnetic field, several different approaches have been used (see Genevey et al. 2008). For example, Coe (1967) modified the Thellier–Thellier method, including a double heating–cooling step performed first in zero field and then in an applied field, becoming nowadays the most common method for archaeointensity determination. Apart from the classical method of Thellier–Thellier and its modifications, other approaches have been developed. Some are based on the NRM demagnetization by alternating magnetic fields; and others on replacing the thermal demagnetization technique with microwave demagnetization during the heating–cooling cycles of the Thellier–Thellier method. The idea of the microwave method is to magnetize and demagnetize the samples without the application of extreme temperatures and, thus, limit the possible mineral alteration. More recently, the multispecimen method has been introduced. This method consists of the heating of a series of sister specimens to a single step of temperature selected according to the blocking temperature. A different field strength is applied to each different sister specimen, and archaeointensities are recovered by determining the field for which the difference between the laboratory pTRM and the ancient TRM, normalized over the ancient TRM, is minimized. One advantage of the multispecimen method is that it is quicker than the classical Thellier–Thellier experiments and it presents a lower risk of magnetic alteration. For a complete review of the different archaeointensity methods

see Genevey et al. (2008) or Dunlop (2011) and references therein.

One of the major weaknesses of the Thellier–Thellier method and its modifications is the mineralogical alteration of the samples during the laboratory protocols. New magnetic phases can appear when Fe-rich materials such as clays, which are rather common in archaeological features, are heated to high temperatures. For this reason, it is a key point to control and test the alteration of the magnetic mineralogy during the experimental procedure. pTRM-check tests, first introduced by Thellier and Thellier (1959), estimate the stability of the TRM and are the most efficient method for detecting magnetic alteration during archaeointensity experiments constraining the reliability of the intensity results. Such tests, however, have not always been performed, especially for data acquired before 1985.

Other important factors that must be taken into account in archaeointensity experiments are the anisotropy of the TRM and the cooling rate dependence of the TRM acquisition. The first effect (denoted as ATRM) can be particularly important for ceramic fragments, tiles, and some other archaeological baked artifacts (e.g., pipes) and reach, in some cases, very high correction factors of more than 70 percent of the determined field strength. In most cases, the ATRM effect is evaluated directly via determination of the TRM anisotropy tensor. An alternative is to adjust the direction of the laboratory field to produce a TRM parallel to the NRM. Other methods can be found in the review paper of Genevey et al. (2008). The second factor, the cooling rate dependence of TRM acquisition with cooling time, can be important when laboratory cooling times (usually of about 1.5 h) are very different to the cooling time of the ancient firing. The cooling rate dependence of TRM intensity can be determined experimentally by measuring additional TRM acquisition steps at different cooling rates. Some authors judge that this correction is unnecessary in their study because the experimental and the original cooling rates are considered similar, and in some laboratory protocols the effect is automatically corrected. However, in the majority of the archaeointensity studies, data are derived from pottery fragments or structures for which the original cooling time is unknown (from an archaeological point of view). The adequate

correction of this effect is, therefore, a major challenge nowadays. In any case, the evaluation of this effect is not made for almost 80 percent of the data of the recent archaeointensity dataset (Genevey et al. 2008).

Present and future challenges

The most recent compilation of archaeointensity data is Geomag50.v3 (Brown et al. 2015). This database contains all the available archaeointensity data for the Holocene together with their corresponding information (such as the laboratory procedure followed to estimate the paleointensities and the associated dating methods and uncertainties). As mentioned previously, the archaeointensity data, along with the directional field, declination, and inclination, present a very inhomogeneous spatial and temporal distribution for the Holocene period (last 12,000 years). About 50 percent of the archaeomagnetic data come from sites with ages between 650 and 1900 CE and only 17 percent of them correspond to ages before 1000 BCE. This percentage is reduced to 2 percent for ages prior to 5000 BCE. The majority of archaeointensity determinations correspond to the northern hemisphere (~96% of the total), with the highest density of data in the European continent. However, great effort is being made to collect data from new areas from the southern hemisphere, such as Central–Southern America, Africa, and Oceania (see Brown et al. 2015 and references therein), where new sets of archaeointensity data are emerging.

In addition to the low number and poor spatial and temporal distribution of data, there is another main problem: the high scatter observed in regional databases, which clearly indicates that some of the data available in the databases might not be reliable, as has been argued in different studies. During the last years, in an effort to obtain a high-resolution description of past geomagnetic field intensity changes at regional scales, different authors applied selection criteria to estimate the reliability of available archaeointensity data. In some of these studies the authors even considered some of the data as unreliable and rejected them in their interpretation of past geomagnetic field variations. This is, perhaps, an extreme point of view, but it underlines the need to develop

robust palaeomagnetic criteria for evaluating the reliability of the intensity estimations contained in the databases before using them for modeling the past variation of the geomagnetic field.

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Archaeomagnetic Dating of Baked Clay Features

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Basics and principles

When archaeological finds and historical documents do not allow one to establish absolute chronologies, natural science dating methods are needed which provide an age on human timescales. Among others (e.g., radiocarbon, dendrochronology, or thermoluminescence (see THERMOLUMINESCENCE) dating), the archaeomagnetism (see ARCHAEO-MAGNETISM) of baked clay features can be used to do so. The various methods have different advantages and drawbacks, leading to an uncertainty in age which has to be taken into account. In other words, each method provides an interval of age within which the feature dates with a certain probability. One major advantage of archaeomagnetic dating is that in most cases the activity of our ancestors is directly dated. The method needs a calibration curve that is built from archaeomagnetic data obtained from independently well-dated baked clay features. Nevertheless, the method may also be used to establish relative chronologies when data from several features at a site are compared or the trend of the geomagnetic variation is roughly known from global models.

At the Earth's surface the geomagnetic field can roughly be described as the field of a geocentric dipole (very short bar magnet) inclined with respect to the rotation axis. Non-dipole terms are also relevant, and both parts slowly change with time. At a location the geomagnetic field vector is described by three components. The field direction is represented by declination (D), the direction of the magnetic compass relative to geographic North, while inclination (I) is the tilt of the magnetic field line. The field's strength is called intensity (F). When the direction moves, D and I increase or decrease as well as F on

timescales of decades to millennia. This phenomenon is called geomagnetic secular variation. Archaeomagnetic dating of baked clay features can use one, two or three of these components describing the field. Because secular variation does not show a simple trend on timescales of several centuries to millennia, archaeomagnetic dating may be ambiguous, especially when only one magnetic component is used.

Materials and sampling

Although some earlier magnetic investigations on baked clay features exist, Emile and Odette Thellier were the first to gain international recognition for systematic research with the aim of using archaeomagnetism for dating. Regardless of whether accidentally or intentionally exposed to heat of at least several hundred degrees Celsius (best if greater than 600°C), any archaeological feature or find of clay, loam, soil, or rock, in principle, can be used for archaeomagnetic dating. These are in situ features like hearths, any kind of fireplace, ovens, kilns, or furnaces which were used for domestic fires, production of pottery, brick, lime, metal, glass, or such like, as well as layers of burn caused by intense fire. Suitable displaced materials are ceramics like pottery, bricks, tiles, tuyeres, daub, or whorls made of baked clay. While in situ features can provide all three vector components, the archaeomagnetic direction at the site is lost as soon as the material has been displaced after cooling.

Dating usually uses the archaeodirection. This requires oriented samples to be taken from the baked clay feature which remained in situ since its last heating and cooling in the geomagnetic field. Any disturbance (e.g., tilting) would cause an error of the measured archaeomagnetic direction and hence corrupt the dating. Displaced baked clay material like bricks or pottery may allow measurement of the inclination when reasonable assumptions can be made about how they were oriented during the firing process. However, such material is often very suited for determination of the archaeointensity (see ARCHAEOINTENSITY)

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recommended as a second or third parameter for dating. Weakly baked clay is not suited for archaeointensity measurements, but may be used for determination of the direction because it is partially remagnetized.

For determination of archaeodirection, at least 6 but preferably 15–25 independently oriented samples spread over the feature are recommended. Depending on the hardness of the baked clay, they can be taken using different techniques, such as blocks covered with plaster, drill or soft cores, small pieces with an orientation mark glued on it, or plastic containers pushed into the material (e.g., Trapanese, Batt, and Schnepf 2008, and references therein). Apart from geographical coordinates of the site, the orientation of each sample in space is required. This is achieved by applying a fiducial mark (arrow), of which the angle with respect to geographic North and the dip with respect to the horizontal plane are measured before removing the sample. The simplest orientation is installing a horizontal plane on the sample block and marking magnetic North precisely using a compass. More sophisticated techniques require special instruments.

Experimental procedures

While small pieces or plastic containers provide samples that are ready to measure, large samples of unconsolidated baked clay may need consolidation in the laboratory first, before blocks or cores are cut into specimens of usually about 10 cm³ volume. Laboratory procedures may include measurements of rock magnetic parameters for characterization of the magnetic particles. Determination of the so-called characteristic direction of the specimen is essential, since this is a measure of the archaeomagnetic field direction during the last cooling of the feature. The standard procedure is to determine the initial magnetization and to demagnetize it by heating or alternating magnetic fields. The demagnetization series is used to find the characteristic direction with principal components analysis. Demagnetization is necessary because the initial magnetization may have overprints of different origins, or weakly baked clay may only carry

a partial thermoremanent magnetization. All directions are then combined to give a feature mean. It is recommended to calculate this mean archaeomagnetic direction in a hierarchical process by averaging first the results of all specimens at a sample level and then on a feature level (Lanos et al. 2005). This mean direction (D and I) is characterized by three parameters: number of independently oriented samples ($n \geq 5$), confidence circle ($\alpha_{95} \leq 5$), and precision parameter of the Fisher statistics ($k \geq 50$). Well-defined archaeomagnetic directions should respect the limits given in brackets. As α_{95} decreases with increasing n , values of the order of 1° or less can be reached. When only a few samples are measured, a large k (≥ 200) indicates a precise measurement although α_{95} may be as high as several degrees. The archaeomagnetic direction may be accompanied by the archaeointensity which is much more laborious and experimentally difficult to obtain.

Dating

For the dating procedure D, I, and/or F are used for comparing them with appropriate calibration curves for the region. This is done by using software (Pavón-Carrasco et al. 2011; Lanos et al. 2005) that calculates, for example, the overlap of the archaeodirection's confidence circle with the confidence band of the directional calibration curve. Normally the confidence limit is set to 95%, which means that the age of the feature lies with 95% probability within the dating interval provided by the software. Using the archaeointensity as a third parameter can increase the precision of the dating considerably, when a suitable calibration curve is available. The precision of dating is strongly dependent on the time period in question. Similar to the plateau effect of radio-carbon dating, the directional archaeomagnetic calibration curves form cusps or loops in which the direction of the baked clay feature may lie. Then a large age interval will be obtained which can last several hundreds of years. In contrast, the dating error may be pretty small if the direction lies outside the loop or if secular variation was rather slow. Another problem is that the dating may be ambiguous because the directional secular variation rarely departs more than ca. 20°

from the axial dipole field direction, while the variation of archaeointensity is generally of the order of plus or minus 50% of the present-day value. This means that the geomagnetic field recovers a very similar direction and/or intensity after a certain time. This is the case in Germany for late medieval and Roman times, or for Iberia around 550 and 1600 CE (Gómez-Paccard et al. 2006). Here, prior archaeological information must help to restrict the possible dating interval. Archaeomagnetic dating in regions or time intervals not yet covered with archaeomagnetic data is possible by using calibration curves obtained from global modeling of the secular variation (e.g., Pavón-Carrasco et al. 2011, and references therein). But such results have to be used with caution because the calibration curves are much less well constrained, may be biased, and because of the ambiguity mentioned above.

The most commonly used scientific dating method may be radiocarbon dating, which becomes very imprecise because of calibration curve plateaus caused by variation in the radiocarbon production rate. Archaeomagnetic dating may have the potential to overcome this particular problem because it seems to be most precise in such periods. During the Early Medieval and Hallstatt radiocarbon plateaus, the archaeomagnetic field shows, at least in Europe, a relatively strong movement of direction accompanied by strong and rapid variations in archaeointensity (Genevey et al. 2016; Hervé, Chauvin, and Lanos 2013).

Calibration curves

Development of a calibration curve requires data from a region with a typical radius of 500–1,000 km, and from several centuries or millennia, covering each century with a minimum of two data points. For curve calculation, the state of the art is represented by sliding window or Bayesian (see BAYESIAN STATISTICS) statistical techniques which provide continuous curves of declination, inclination and/or intensity, and take into account prior knowledge such as error of age and magnetic parameters or stratigraphy (e.g., Lanos et al. 2005).

Global calibration curve models use the various databases built for archaeomagnetism (e.g., Arneitz et al. 2017). The Bayesian curve building itself is also able to provide *a posteriori* dating for each feature involved (Lanos 2004).

SEE ALSO: Archaeointensity; Archaeomagnetism; Radiocarbon Calibration and Age Estimation

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Archaeomagnetism

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Introduction

Archaeomagnetism, the study and interpretation of the magnetic properties of archaeological baked materials, is an interdisciplinary topic that requires expertise both in geophysics and in archaeology. From the study of the *thermoremanent magnetization* acquired by well-dated archaeological features, geophysicists have established master curves of the variation of the geomagnetic field for a particular region. Once established, these curves can be used as a dating tool for undated baked archaeological materials. *Archaeomagnetic dating* is probably the best known application of paleomagnetism to archaeology, but the study of the magnetic properties of archaeological materials also provides a wealth of information, including insight into their composition, provenance, and paleofiring conditions. Successful archaeomagnetic research thus depends on input from these two domains and, in turn, archaeomagnetism is capable of providing useful information to both disciplines. This technique is based on the capacity of certain archaeological materials that are rich in iron oxides, heated to several hundred degrees Celsius, to retain a stable *thermoremanent magnetization*. This magnetization is locked in the archaeological material until further heating, and preserves information on the direction and intensity of the past geomagnetic field at the place and time of the last heating-cooling cycle. If the date of the last firing of the archaeological feature is known and the thermoremanent magnetization remains unaltered throughout the time period between its acquisition (the last heating of the feature)

and the moment of measuring the archaeological sample, it can be used to make an indirect observation of the past geomagnetic field vector for a particular location and specific time.

Physical background

The basic phenomenon that makes archaeomagnetism possible is the ability of certain archaeological clay-rich materials heated to high temperatures to preserve information about the ambient magnetic field present at time of their last cooling, which is usually the Earth's magnetic field. If materials that are rich in iron oxides (e.g., magnetite, Fe_3O_4 , and maghaemite, $\gamma\text{-Fe}_2\text{O}_3$) are heated above a certain temperature (the so-called *Curie temperature*, which is characteristic for each magnetic mineral), they become easily magnetized in the direction of the ambient geomagnetic field. On subsequent cooling below the blocking temperature, this magnetization (the thermoremanent magnetization, TRM) is locked in the material until further heating and, under certain circumstances, is also proportional to the ancient magnetic field. Iron oxides are ubiquitous in most of the clay deposits that were used in the past for the construction of archaeological features (e.g., kilns, furnaces, ovens). In addition, during their heatings, these structures often exceed the Curie temperatures of magnetite (578°C) and maghaemite ($578\text{--}675^\circ\text{C}$). Even if the original clays were not rich in such iron oxides, the heating and cooling cycles may have produced them due to thermally induced mineralogical transformations. The processes by which archaeological materials become magnetized are well founded in the physical theory of thermoremanent magnetization (Néel 1955). This theory explains how grains of magnetic minerals become permanently magnetized as they cool through their magnetic blocking temperatures in the presence of an external field. Because the cooling time for typical archaeological structures is rapid (from some hours to several days), it may be assumed that the archaeological structures provide spot readings

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in time of the geomagnetic field direction and intensity at the time of cooling. TRM acquisition theory also provides a basis for obtaining measurements of the strength or intensity of the field, known as absolute archaeointensity or paleointensity. The study of the TRM acquired by well-dated archaeological baked materials therefore provides a unique way to recover past geomagnetic field variations in the historical past.

Historical overview

Archaeomagnetism has a hybrid origin. It evolved both from the study of the Earth's magnetism and from the study of the magnetic properties of synthetic and natural materials. The study of the origin and behavior of the geomagnetic field is one of the earliest domains of Earth Sciences, with observations made in classical times, and also is the subject of probably the first scientific treatise. In 1269 Petrus Peregrinus wrote his "Epistola", an experimental treatise on the magnetic properties of a spherical lodestone, and was the first to describe the existence of two magnetic poles in magnets. Three centuries later, William Gilbert applied this concept to the Earth, and proposed that the Earth itself acts like a great magnet (*De Magnete*, 1600). Although Gilbert's model explained a considerable part of the static field, after the discovery of the temporal variation of the magnetic declination made by Gellibrand in 1635, a whole new dimension opened up. Since then, different models have been proposed to explain the temporal and spatial variation of the geomagnetic field (see Jonkers 2003 for a review of theories of the field up to 1800). Nowadays, we know that the geomagnetic field is a dynamic phenomenon that varies on a vast range of temporal and spatial scales. The main source of the geomagnetic field is to be found in a dynamo operating in the Earth's electrically conducting iron-rich fluid outer core, about 2900 km below the Earth's surface. This portion of the geomagnetic field is often referred to as the main field. The main field varies slowly with time and space: these changes are called the secular variation of the geomagnetic field. For this reason, in order to get a satisfactory picture, the geomagnetic field must be measured at many places all around the

world. For recent times, this is done by approximately 200 operating magnetic observatories worldwide, and by satellite missions, such as the European Space Agency's magnetic field mission *Swarm* launched in November 2013, which allows observation of the field at unprecedentedly high resolution. Since the sixteenth century, when the expanding number of marine expeditions led to a great increase in the use of the magnetic compass, direct observations of the direction of the geomagnetic field have been available. However, instrumental measurements of the geomagnetic field strength were not routinely available until 1832, when Gauss discovered a method to measure absolute geomagnetic field intensities. Information about geomagnetic field variations prior to direct measurements requires indirect observations of the geomagnetic field that can only be obtained from the paleomagnetic study of well-dated geological or baked archaeological materials that preserve a record of the past geomagnetic field as a remanent magnetization.

The observation that the magnetism can survive in rocks and archaeological materials at historical and geological timescales has proved to be one of the most rewarding discoveries in Earth Sciences. Pioneering work on archaeological artifacts began in the seventeenth century when Boyle (1691) demonstrated that bricks lose their magnetization when heated to high temperature and acquire a new one while cooling. The idea that archaeological materials could be used to extend the geomagnetic record over historical times was known by the last decade of the nineteenth century. Folgheraiter (1899) summarized the method and recovered the magnetic inclination recorded by different archaeological objects. Since the times of Brunhes (1906) it has been known that the TRM acquired by baked clays is parallel to the direction of the geomagnetic field during cooling, and that the TRM remains unaltered even if the Earth's magnetic field changes. Chevallier (1925) applied the same ideas to recover directional geomagnetic field changes from historical lavas from Mount Etna (Italy). The idea of recovering the intensity as well as the direction of the geomagnetic field dates back to Folgheraiter (1899) who proposed that the ratio between the natural remanent magnetization produced by cooling in the ancient field and the TRM after cooling in the present field should be the same as the

ratio of the two fields themselves. About 40 years later, Émile and Odette Thellier produced the first reliable determinations of paleointensity from the study of archaeological materials. They developed a laboratory protocol to determine directions and intensities and indicated a series of conditions (the Thellier laws) that must be fulfilled to reliably determine the intensity of the ancient geomagnetic field. Their work culminated in the physical bases of TRM blocking and recognized the essential role of grain size and shape in the TRM acquisition process. In 1949 Louis Néel quantified these concepts in terms of the properties of single-domain grains (Néel 1955). These methods are still valid and used today (see ARCHAEOINTENSITY).

Procedures

In archaeomagnetism, the geomagnetic field vector is defined by three elements: the declination (D), the inclination (I), and the intensity (F). D is the angle between the geographic North and the horizontal component of the geomagnetic field, ranging from 0° to 360° (or 180°W to 180°E). I is the angle between the horizontal plane and the geomagnetic field vector: it ranges from -90° (up) to 90° (down). The intensity, F, is the vector strength, which nowadays ranges from 25 to 65 μT at the Earth's surface. The aim of archaeomagnetic research is to determine the values of these three elements from the magnetic study of archaeological baked materials.

For this purpose, when an archaeological feature is excavated, several oriented samples should be recovered and the TRM measured in a paleomagnetic laboratory. During this process, the reference direction must be preserved to determine the directional elements (i.e., D and I). That is not the case for intensity measurements, for which non-oriented samples can be considered. If one takes into account that the secular variation of the geomagnetic field direction is of the order of a few degrees within tenths of years, the precision of the orientation during sampling should be less than 1–2°, if possible. In this context, the most precise sampling method is to use pouring gypsum to create a horizontal surface where a reference direction is marked by means

of a solar or magnetic compass. It should be highlighted that when the structures are strongly magnetized, the use of a magnetic compass may produce important biases. Most remanence measuring equipments require regularly shaped specimens. Therefore, hand samples are generally impregnated in water-glass or ethyl-silicate in order to consolidate the samples before cutting standard cubes or cylinders. Drilled cylinders can also be directly obtained from the archaeological structures, if the materials are well consolidated.

Once prepared, these specimens are treated at the paleomagnetic laboratories following different protocols that have been established to guarantee the precise measurement of the past geomagnetic field direction. Such techniques involve stepwise demagnetization procedures. The main objective of these demagnetization protocols is to detect possible secondary records that should be subtracted to properly determine the characteristic remanent magnetization acquired during the last heating/cooling of the archaeological structure. The mean direction is derived from Fisherian analysis of several specimens per structure, and is given together with its corresponding error (see Tauxe et al. 2014 for further details). If the date of the last firing of the archaeological feature is known, the direction (D, I) of the geomagnetic field in the past for that location and specific time can be estimated. In contrast to the directional studies, which are nowadays well established, the archaeointensity determination is more complex. Up to now, there have been different proposed methods to measure the archaeointensity, with the consensus that the Thellier and Thellier (1959) derived methods yield the most reliable paleointensity determinations. These methods are based on the progressive replacement of the natural remanent magnetization of the samples (acquired in the past) by an artificial TRM acquired in a known field. Different laboratory tests should be applied in order to assure the reliability of the ancient field intensity estimation (see ARCHAEOINTENSITY). This geomagnetic element has an advantage over the directional elements (i.e., declination and inclination) because it does not require oriented samples. For this reason, baked clay objects such as fired bricks, potteries, tiles, or shards, that also exhibit a TRM, can be used to derive archaeointensities.

Archaeological applications

In archaeology, dates are often derived from different methods simultaneously, ranging from conventional archaeological typological determinations over radiocarbon or luminescence dating methods. In this context, the wealth of information stored in the magnetic record can certainly make an important contribution. The compilation of archaeomagnetic data from a particular region allows the construction of time-continuous paleosecular variation (PSV) curves. These PSV curves provide an additional dating tool (see *ARCHAEOMAGNETIC DATING OF BAKED CLAY FEATURES*) that can be an important part of an integrated archaeological dating strategy (see *DATING IN ARCHAEOLOGY*). Archaeomagnetic dating (see *ARCHAEOMAGNETIC DATING OF BAKED CLAY FEATURES*) consists of the statistical comparison of the archaeomagnetic field information obtained from an undated archaeological structure with the corresponding PSV curve. Due to the spatial and temporal variability of the geomagnetic field, the PSV curves may vary significantly from one continent to another, and therefore for dating purposes the curves need to be defined for each particular region. In this sense, the archaeomagnetic dating tool can only be reliably applied in regions with well-constrained PSV curves. The precision of archaeomagnetic dating depends on several factors and varies from case to case. The most significant are: the rate of variation of the geomagnetic field, the envelope errors of the master curve, and the error in the archaeomagnetic data derived from the undated archaeological material. It is worth pointing out that the accuracy of the PSV curves depends on the temporal and measurement uncertainties of the archaeomagnetic data on which the curves are based, and on the number of structures available for each period. This indicates not only the need to obtain additional data, but also the importance of studying well-dated materials in order to better constrain the PSV reference curves.

Archaeomagnetic dating is probably the most known application of archaeomagnetism to archaeology, but the study of the magnetic properties of archaeological materials also provides a wealth of information, including insight into their composition, provenance, and paleo-firing conditions. For example, anthropogenic

cave sediments usually contain multiple burning events that can be magnetically studied to determine the temperature of the last heating undergone by the materials, to evaluate to what extent a burning event might be affected by post-depositional processes, or to identify temporal differences between different combustion events (see Carrancho, Herrejón-Lagunilla, and Vergès 2016 for further details).

State-of-the-art and future challenges

Since the pioneering archaeomagnetic studies performed in the second half of the twentieth century, the techniques of archaeomagnetism have been extended and developed. The production of new archaeomagnetic data has strongly increased during the last years (see Brown et al. 2015 for a recent compilation). As a direct result, different regional PSV curves for the three geomagnetic field elements (D, I, and F) are now available, particularly in Europe, the Middle East, Japan, Korea, central and southwestern North America. Different statistical techniques such as moving-average running windows, Bayesian statistics, bootstrap algorithms, or the Markov chain Monte Carlo method are applied to obtain these PSV curves. These curves are currently used for dating purposes. Recent archaeointensity studies show that the geomagnetic field has exhibited numerous short-lived, regional maxima in intensity at various times and locations. These phenomena, not captured by current global geomagnetic field models due to their limited temporal resolution, are still poorly understood. More archaeointensity data are essential to gain insight into the spatial and temporal evolution of these intriguing phenomena. At global scales, archaeomagnetic data have been used to generate continuous spherical harmonic geomagnetic field models, which allow reconstruction of past changes in the geomagnetic field not only at the Earth's surface, but also at the core-mantle boundary. For this reason these models are of invaluable interest for scrutinizing core dynamics over centennial and millennial timescales. The robustness of geomagnetic field models is limited by uncertainties arising from geographical and temporal sampling biases in current databases. In particular, the crucial importance of improving

data coverage for the Southern Hemisphere has been recognized, since the number of data for this region is still too low to infer a reliable estimation of past geomagnetic field changes. Another important issue that should be resolved in the near future is to establish a set of criteria that guarantee the reliability of archaeomagnetic data before using them for modeling purposes. It is safe to say that the more replicate specimens that are measured, and the more samples from different recording media that are measured yielding consistent results, the more confidence we can have in the final result. Recent results confirm the crucial relevance of TRM anisotropy corrections when studying past geomagnetic field strength of highly anisotropic objects such as pottery or bricks. Biases of more than 50% in archaeointensity estimations are often observed if this correction is not properly applied. Future studies must focus on the acquisition of new high-quality data from unexplored regions.

SEE ALSO: Archaeointensity; Archaeomagnetic Dating of Baked Clay Features; Dating in Archaeology

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FURTHER READINGS

Argon–Argon Dating

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Introduction

The argon–argon dating method (Ar–Ar hereafter) is based on the same radioisotopic decay system as ^{40}K – ^{40}Ar dating (K–Ar hereafter). It is based on the natural, spontaneous radioactive decay of an isotope of potassium, ^{40}K , at a known rate, to produce an isotope of argon, ^{40}Ar . The Ar–Ar method was established by Merrihue and Turner (1966), and led to improvements that eliminate problems intrinsic to the K–Ar method. The terrestrial abundance of the parent isotope, ^{40}K , and the slow rate of its decay (1.25×10^9 years), combined with numerous technical and procedural improvements, especially the single-crystal total-fusion approach developed more than 25 years ago, have made this method one of the most versatile, precise and accurate of all radioisotopic dating tools applied to volcanic materials. Ar–Ar age uncertainties are usually given at the $\pm 95\%$ confidence level or otherwise specified. It is now usual to find Quaternary ages with absolute precision and accuracy $< 0.5\%$.

Basis

^{40}K undergoes branched decay by two modes (Steiger and Jäger 1977) into ^{40}Ca ($\lambda_\beta = 4.962 \pm 0.009 \times 10^{-10}$ y) and to ^{40}Ar ($\lambda_\epsilon = 5.808 \pm 0.004 \times 10^{-11}$ y). The decay of ^{40}K into ^{40}Ar is expressed by a total decay constant, λ , that is the sum of decay constants, $\lambda_\beta + \lambda_\epsilon$ ($\lambda = 5.543 \pm 0.010 \times 10^{-10}$ y). The proportions of K isotopes at any time in Earth history are uniform, with the following percentages: $^{41}\text{K} = 6.7302\%$; $^{40}\text{K} = 0.01167\%$; $^{39}\text{K} = 93.2581\%$. Argon is variable over time in isotopic composition because of its radiogenic

production ($^{40}\text{Ar}^*$) from ^{40}K as described in Equation (1). The atmosphere (“air” hereafter) contains isotopically homogeneous Ar, with abundances of ^{36}Ar , ^{38}Ar , and ^{40}Ar with percentages of $0.3336\% \pm 0.0004$, $0.0629\% \pm 0.0001$ and $99.6035\% \pm 0.0004$ respectively (Lee et al. 2006). From Equation (1), it is possible to derive the basic age Equation (2).

$$^{40}\text{Ar}^* = \lambda / \lambda_\epsilon \, ^{40}\text{K} (e^{-\lambda t} - 1) \quad (1)$$

$$t = 1/\lambda \ln [^{40}\text{Ar}^*/^{40}\text{K} (\lambda/\lambda_\epsilon) + 1] \quad (2)$$

The $^{40}\text{Ar}^*$ produced after a volcanic eruption (daughter), as well as the quantity of ^{40}K remaining (parent), must be determined in order to calculate a sample age (see Equation (2)). To determine the concentration of $^{40}\text{Ar}^*$ in a sample, a noble-gas mass spectrometer is used. First, the total abundance of ^{40}Ar ($^{40}\text{Ar}_t$) in the sample should be measured and then corrected for the portion that is non-radiogenic, i.e. the initial ^{40}Ar ($^{40}\text{Ar}_i$) present in the sample as shown in Equation (3):

$$^{40}\text{Ar}^* = ^{40}\text{Ar}_t - ^{40}\text{Ar}_i \quad (3)$$

Correction for $^{40}\text{Ar}_i$ is made by assuming that all of this argon is associated with ^{36}Ar (also measured by mass spectrometry) in the proportion $^{40}\text{Ar}/^{36}\text{Ar} = 298.56$ (atmospheric ratio). Therefore, to calculate $^{40}\text{Ar}^*$ one simply subtracts 298.56 times the ^{36}Ar from the $^{40}\text{Ar}_t$. The quantity of ^{40}Ar left from this calculation is known as the “percent radiogenic”. It is documented that some rocks contain “excess” argon, with $^{40}\text{Ar}/^{36}\text{Ar} \ll 298.56$, resulting in spuriously older ages. The Ar–Ar method allows one to test whether the $^{40}\text{Ar}_i$ is atmospheric using isochron approaches. However, the air correction is likely to be valid with rocks that have been in contact with the atmosphere, such as eruptive volcanic materials. The determination of the parent (^{40}K) is not direct and requires neutron activation of ^{39}K to ^{39}Ar by a process known as electron capture. ^{39}Ar can be measured by mass spectrometry along with the other isotopes of argon (^{40}Ar ,

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^{38}Ar , ^{37}Ar , and ^{36}Ar). This allows a more precise measurement of both the parent and daughter products at the same time, using typically less than 1 mg of material. The reaction requires fast neutrons ($<1.4\text{ MeV}$ electrons) and the use of a nuclear reactor to irradiate the sample. The neutron-induced ^{39}Ar ($^{39}\text{Ar}_K$ hereafter) is directly proportional to the concentration of ^{39}K in the sample and thus indirectly proportional to the desired ^{40}K because of the consistency of the isotopic composition of K. In order to quantify the neutron fluence parameter, J , during irradiation it is necessary to measure the Ar isotopic composition, i.e., $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ of a standard of known age that received the same neutron dose as the sample, that is, Equation (4). The two most widely used inter-laboratory standards for Plio-Pleistocene samples are Alder Creek sanidine (ACs-2) and Fish Canyon sanidine (FCs) with ages of about 1.1848 and 28.201 Ma respectively (Niespolo et al. 2017). The J value calculated for every sample is integrated to Equation (2) to solve the age of a sample, as illustrated in Equation (5). The $^{40}\text{Ar}^*/^{39}\text{Ar}_K$ ratio is measured in the sample by mass spectrometry.

$$J = (e^{-\lambda t} - 1) / ^{40}\text{Ar}^* / ^{39}\text{Ar}_K \quad (4)$$

$$t = 1/\lambda \ln [J ^{40}\text{Ar}^* / ^{39}\text{Ar}_K + 1] \quad (5)$$

Precision and limits

The Ar–Ar age precision and accuracy are directly related to the standard used. As a result, establishing the “true” age of standards is a very active research field. The neutron irradiation of geological material produces, in addition to ^{39}Ar , various Ar isotopes from K and Ca isotopes. These are known as “nucleogenic interferences”. These interfering Ar isotopes are measured in the sample and corrections applied using simple and pure synthetic material, such as CaF_2 and KFeSiO_2 glass, irradiated in the same reactor. These corrections are very important for young samples and/or samples with high Ca (the main source of error), explaining why low-K and/or high-Ca-bearing rocks are more difficult to date with the Ar–Ar method. Other λ values are used in the current literature, and the ages of ACs and

FCs standards given above may also slightly vary in the literature but only within 1%. Nevertheless, it is easy to recalculate the age of a sample based on a given standard age and decay constant. The $^{39}\text{Ar}_K$ formed in the reactor can recoil and can cause redistribution and/or loss of $^{39}\text{Ar}_K$ in the sample, leading to spurious older ages. The distance of recoil and quantity of $^{39}\text{Ar}_K$ lost is usually very small ($\ll 1\%$), but may be an issue in very small ($<50\text{ }\mu\text{m}$) or high volume-to-surface ratio samples. This problem explains why clay minerals and glass shards are not well suited for the Ar/Ar method.

Technical developments

Technical developments in mass spectrometry and detectors over the last 25 years now enable the calculation of an age using only Ar isotopes extracted from extremely small Pliocene and Pleistocene samples, down to individual single crystals ($<500\text{ }\mu\text{m}$ in size). This capacity has been used since the early 1990s by total fusion of single crystals, and was used initially to tackle archaeological questions. The advantage of this approach is that pyroclastic material can be dated without having been biased by xenocryst contamination. Minerals such as sanidine, leucite, biotite and hornblende are the most commonly used minerals in the Ar–Ar single-crystal approach. It is usual to depict single-crystal dating results by a mean of an age-probability diagram (Deino and Potts 1992). Such a plot is convenient for highlighting populations of crystals sharing the same age. Generally, it is accepted that the youngest crystal population corresponds to juvenile ones, and the other modes to xenocrysts. The weighted mean age of all crystals from the youngest mode is used to calculate the age of the eruption. The most recent mass spectrometers equipped with highly sensitive ion-beam multicollectors allow the dating of Lower Pleistocene single crystals of K-feldspar (sanidine, leucite) of $250\text{--}300\text{ }\mu\text{m}$ and less than 100 ka in only ten minutes. The Ar–Ar method overlapping with ^{14}C dating in the 15–40 ka range permits the intercalibration of these methods (Giaccio et al. 2017). Compared with the U–Th method, the Ar–Ar method is less versatile with respect to materials, but applicable,

unlike U–Th, to most of the Quaternary. Compared with other methods used in archaeology, such as electron-spin resonance, thermoluminescence or cosmogenic dating, the Ar–Ar method is currently more reliable and precise because most of the method's underlying assumptions are testable. In short, today, the only real limiting factor is the presence of volcanic material in an archaeological site.

Applications

Since Ar–Ar dating can only be used to date volcanic material, it is widely applied from the Plio-Pleistocene period in areas where volcanic activity is coeval with archaeological remains, such as Eastern Asia, Africa, and southeastern Europe. In archeological settings, two general cases can be found: (1) The archeological remains/traces are found embedded in a primary volcanic deposit, such as tuff, ignimbrite or lahar. In that simple case, which is rather rare, the age of the archaeological remains will be given by the age of the volcanic deposit. An example of such a case is the hominid footprints found in Laetoli (Tanzania; Deino 2011) dated at 3.66 ± 0.02 Ma, the direct age of the tuff where the footprints were found. (2) In many instances, the archeological level(s) are found sandwiched between volcanic deposits (i.e., tephra layers), which, if properly dated by Ar–Ar, will provide a bracketing age of the deposition of the sedimentary layer(s) containing the archaeological remains. A example is the remains of *Ardipithecus ramidus* (Middle Awash, Ethiopia) found in a sedimentary layer between the Gaala basal tuff and the Daam Aatu Tuff, dated by Ar–Ar at 4.419 ± 0.068 Ma and 4.416 ± 0.031 Ma respectively (WoldeGabriel et al. 2009). The very low quantity of material now needed for Ar–Ar dating also allows the use of this method as a forensic tool to identify the origin of raw material, such as obsidian (Vogel et al. 2006). Overall, Ar–Ar dating has greatly improved in precision and accuracy over the last 10 years, making it possible to work with smaller and/or younger minerals. As a result, more distal volcanic materials that could be found in archaeological sequences are now accessible to direct dating.

However, there is still a size limitation that could be overcome if the volcanic deposit could be chemically identified and therefore tied to a known eruption dated by Ar–Ar.

SEE ALSO: Cosmogenic Dating; Dating and Electron Spin Resonance (ESR); Tephra and Volcanic Ash Analysis; Thermoluminescence; Uranium-Series; Volcanic Rock Sourcing

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Climate Change and Dating

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Recent weather events including catastrophic hurricanes, flooding, and unusually warm or cold air spells have raised significant popular awareness of the notion of climate change. The main unknowns resolve around whether we are living in a changing climate with higher risks of extreme weather than usual, or whether the climate has changed to the extent that its long-term variability is perceptible to the human observer (IPCC 2013).

Climate in a narrow sense represents the average daily or seasonal weather, but it also involves the statistical description in terms of the mean and variability of a range of near-surface physical variables, including the amount and distribution of solar irradiation, air temperature, rainfall, and wind stress. Shifts in the mode of operation of such variables over different periods of time resulting from heat exchange between land and oceans are regionally defined as weather patterns. The most significant manifestations of weather patterns that we observe today include the seasonal recurrence of monsoons in Asia, the tropical storm belts, the El Niño Southern Oscillation that affects mainly the Americas, the North Atlantic Oscillation, and the Gulf Stream, the latter responsible for the mild winter temperatures over Europe.

As the biosphere, hydrosphere, and atmosphere are all closely interconnected in defining local, regional, and global climate trends, any disturbance affecting one or more major variables may bring about rapid, sometimes even abrupt environmental shifts. This complexity in

its manifestation defines climate change as a shift in the state of the global system that persists for an extended period of time, typically decades or longer. On longer timescales, the earth system's continuously dynamic evolution is driven by some major climate-defining players including astronomical modulation of solar irradiation, ocean heat balance and salinity changes, greenhouse gas forcing, and orographic and ice-volume fluctuations.

Various proxy data, nowadays extensively coupled with modeling experiments, are being employed in testing and simulating new hypotheses about climate variability. For example, it has been suggested that climate variability continuously shaped the distribution, composition, and vulnerability of various components of the global ecosystem (see PALEOENVIRONMENTAL RECONSTRUCTION), including humans and their material cultures they established globally. However, an issue that still compels considerable research effort is the timing of past climate events in paleoclimate records worldwide. Exploring the relationship between various modes of operation active within the climate system at any given time and location is persuasive, but the resolution and sensitivity of dating methods (see OPTICALLY STIMULATED LUMINESCENCE and DATING AND OPTICALLY STIMULATED LUMINESCENCE) applicable to any particular paleoclimate record play an equally critical role.

Looking at the past: the nature of climate change during the Quaternary

Several hypotheses have been put forward in explaining the emerging evidence of past climate variability. The major variables involved are astronomical modulation of solar insolation that drives major and long-lasting climate variability, such as the glacial–interglacial cycles, a specific feature of Quaternary climate change, to decadal and seasonal fluctuations in solar irradiance, rainfall, temperature, and runoff that are more easily perceptible to the human

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observer as contemporaneous weather patterns. Quaternary climate change, its causes and regional imprint, has been the focus of substantial research since Milankovitch formulated the astronomical theory of climate. Collectively termed astronomical parameters, the eccentricity, the obliquity, and the precession of equinoxes denote variables in the earth's orbit and inclination of its axis that modulate the amount and spatial distribution of energy received from the sun. Their cumulate long-term effect is seen in the reconstructed periodicity of change, with a combination of 100-ka, 41-ka, and 23-ka cycles accounted for in paleoclimate records covering the last million years. However, orbital parameters are only one driver of major climate changes, with biogeochemical processes operating at the earth's surface and linked to gas (particularly CO_2 and CH_4), with atmospheric forcing likely playing an equally important role (Paillard 2010).

In this respect, marine sediment and ice core research has proven fundamental in our understanding of the pacing and nature of past climate change and paleoclimate sensitivity. Extensive research on marine records greatly increased the understanding of the effects of glaciation on global climates, indicating, for example, that climate changes during the transition towards the present interglacial were unexpectedly abrupt. Prior to this, most paleoenvironmental reconstructions focused on Holocene records, whose quasi-stable interglacial climate did not offer true analogs for the rapid climate variations and ecosystem dynamics that characterized glacial times. Very detailed reconstructions of past local and global mean temperatures and moisture source variations are now available for the last 800 ka from ice cores (Lang and Wolf 2011). High seasonal accumulation of snow, such as in Greenland, even allowed for seasonal time resolution for most proxy records, which provided unprecedented views on the rate of magnitude of change undergone by the global climate system during, for example, the Last Glacial Cycle.

Millennial-scale climate variability as seen in paleoclimate records

Dansgaard–Oeschger (DO) cycles

The typical feature of DO cycles is the rapid temperature increase from glacial levels to maximum warmth attained within a few decades, followed by a gradual cooling trend, terminated with a distinct cold phase lasting for centuries (Lang and Wolff 2011). Even though all DO events exhibit such variability, they vary significantly in terms of duration—from millennia to several centuries. They also appear to be grouped into larger cycles, the so-called Bond cycles, which comprise several DO events and culminated with the deposition of Heinrich layers as ice-rafted detritus in the Atlantic.

The paleoclimatic signal reconstructed from Greenland ice was extreme, with rapid air temperature shifts between stadials and interstadials of 5–16 °C, if not larger. These findings contrast with the early views of gradually decreasing insolation and slowly increasing global ice volumes throughout the Last Glacial Cycle. Unequivocally, such abrupt shifts between cold and warm conditions resulted in repeatedly unbalanced thresholds, forcing adaptation strategies for the broader ecosystem, including the Paleolithic human species.

Observational data and modeled scenarios suggest that DO cycles were triggered by shifts in the thermohaline circulation and the amount of heat delivered to the North Atlantic region by the combined ocean–atmosphere system (Ganopolski and Rahmstorf 2001). The reconstructed pattern of change suggests that a slowdown or complete cessation of deep-water formation and reduced poleward heat transfer are linked with stadial conditions; conversely, an enhanced thermohaline circulation similar to today was active during interstadials. Concurrent variations in the concentration of greenhouse gases and dust, as reconstructed from ice cores, suggest that all components of the climate system participated at least in the propagation of DO events, rendering it rather difficult to assert the triggering mechanisms.

Even more interestingly, the reconstructed interhemispheric pattern of change has a bimodal relationship directly related to changes in the

Atlantic Meridional Overturning Circulation (AMOC) modes, with the polar regions showing opposed paleoclimate signals (Broecker 1998) reflecting the so-called bipolar seesaw mechanism. Whereas Greenland was experiencing warming, the Antarctic region cooled, and vice versa, depending on the regional strength and states of AMOC. Taking a simplistic view, low to medium latitudes in both hemispheres have undergone a range of changes related to the regional imprint of the dominant north or south climate variability, and which, if further modulated by local or regional-scale particularities, such as over the continental interiors, complicate the emerging picture of past climate variability. For example, a range of intermediate signals will be recorded in proxies from the subtropical/temperate region, depending on the strengths and weaknesses of the North Atlantic versus Antarctic influences and related shifts in air circulation and moisture.

Irrespective of the triggering mechanisms, it is apparent that these changes were associated with a latitudinal migration of atmospheric circulation patterns. This resulted in increased zonality and large-scale meteorological shifts in air circulation and rainfall, primarily in the circum North Atlantic region, but also as far as eastern Asia, the Indian Ocean, South America, and the Pacific Ocean. Records from such regions show a very similar pattern of change as that observed in the Greenland ice cores, suggesting that the low-latitude monsoon system may have played an important role in the global teleconnection of millennial-scale climate variations. As such, the DO events as dated and described from the Greenland ice records form a chronostratigraphic template against which paleoclimate and chronological data arising from various other paleoclimate archives are usually tested.

Heinrich layers and Heinrich events

Early studies of marine cores recovered from the seabed of the North Atlantic Ocean led to the identification of peculiar sediment layers, far too coarse for having been transported to the open ocean solely by marine currents (Heinrich 1988). As soon as their nature was understood, the debris layers in the North Atlantic marine

records were linked to ocean-wide disintegration of large amounts of icebergs originating from the neighboring continental ice sheets. A combination of climate–ocean–ice-sheet interactions appears responsible for such periodic surges of icebergs in the North Atlantic, although it is unclear whether they simply reflect mechanics of glacier ice dynamics or climate forcing. Hypotheses have been proposed for explaining their origin, including the destabilization of ice margins by ice-load-induced earthquakes and sea-level fluctuations, the abrupt collapse of the AMOC coupled to subsurface ocean heat transfer into the North Atlantic, abrasion of the ice sheets margins by sea tides, or even catastrophic collapses of ice shelves, similar to what has been observed in recent years in Antarctica (Veres 2007).

The depositional pattern of ice-rafted detritus differs greatly among individual Heinrich layers. For most layers, the rock detritus has been linked through mineralogical screening to the Canadian Shield—evidence that links the majority of icebergs surging to the Laurentide ice sheet via Hudson Bay, where the debris layers attain their maximum thickness (Hemming 2004). Some of the Heinrich layers are characterized by complex depositional patterns, with precursory contributions of ice-rafted detritus typical of Scandinavian–British rock sources. It has been suggested that melt-water and iceberg releases from European precursory events were responsible for an initial reduction of the thermohaline circulation in the North Atlantic, which could have in turn initiated the main collapse of the Laurentide ice sheet. There is also evidence that Heinrich layers were deposited asynchronously in the Nordic Seas, which would suggest significant differences in ice dynamics or in the nature of sediment delivery by ice surging from ice sheets bordering the North Atlantic.

Biostratigraphical, chronological, and isotope modeling data suggest that Heinrich layers—as depositional horizons—accumulated very rapidly (over 500 ± 250 years; Hemming 2004). Heinrich events, on the other hand, encompass a broader time span—a notion that reflects their paleoclimate significance due to their long-lasting influence on sea surface temperature, hydrology, and atmospheric circulation. Data indicate that most Heinrich events strongly affected marine

and terrestrial ecosystems for a much longer duration than the time covered by the actual deposition time of Heinrich layers. In the isotope records from Greenland and Antarctic ice cores, Heinrich events are not distinguishable from other stadials, but as they occurred during the coldest phases of stadials, it may be that the already cold conditions exacerbated the cold climatic signal, with far-reaching consequences. Indeed, the environmental impact caused by the presence of icebergs and melt-water in the Atlantic Ocean is well expressed in marine and terrestrial paleoclimate records. Linked to a complete cessation of the thermohaline circulation, forcing a southward migration of the polar front down to ca 45°N latitude, these phenomena triggered drastic changes in moisture and atmospheric circulation patterns over most of the northern hemisphere, if not globally, albeit with a contrasting pattern of change (Hemming 2004). For example, Heinrich events have been linked to significant sea surface temperature, salinity, and productivity changes in the Atlantic, severely dry and cold events in the Mediterranean region, wet and warm events in the Gulf of Mexico and South America, and even periods of enhanced marine productivity in the Antarctic Seas.

Constraining the timing of rapid climate variability

A consistent picture of environmental change that characterized the Last Glacial Cycle unfolded mainly following the investigation of ice core records. Such data not only allowed for better constraining the timing and amplitude of millennial-scale climate changes, but also highlighted difficulties in chronologically linking data from various records on common timescale(s) (Lang and Wolff 2011). Several timescales have been proposed for polar ice records, and most intensively used in correlating and inferring synchronicity for various proxy data (Bazin et al. 2013). However, even though isotopic data from different ice cores exhibit a remarkably similar pattern in shape and amplitude over various paleoclimate events, when plotted on their individual timescales they diverge significantly. Such differences could occur because

of layer-counting errors and uncertainties in variables resulting from ice-flow modeling. These issues have now been partly solved with the construction of a new timescale for both Greenland and Antarctic records (Bazin et al. 2013), but further refinements are necessary.

Intensive research on marine cores revealed clear similarities in environmental change between such records and ice core data. Few of the marine records rely on strong individual chronologies, mainly because of chronological problems related to the use of radiocarbon dating in marine settings, and dating limitations beyond its range. Most marine records are therefore based on tuning chronological or isotopic tie-points to other records. The main paradigm of such an approach is that changes occurred synchronously, an assumption, however, that can easily lead to a scenario where possibly nonsynchronous events are compared.

For terrestrial sequences such as lake sediments, independent chronologies can be established through radiocarbon and luminescence dating (see DATING AND INFRARED STIMULATED LUMINESCENCE), by using laminated sediments, and by using tephra layers for obtaining critical chronological tie-points. Constraining the relationship between global climate change and local environmental effects, however, remains the subject of ongoing studies.

Holocene climate change

Comprising the last 11.7 ka in the earth's climatic evolution, the current interglacial period, the Holocene, has largely been considered an interval of stable environmental conditions that allowed for the emplacement of current ecotones, as well as the birth and flourishing of humankind. However, following the last deglaciation, multidecadal to millennial climate variations—both warm, such as the Mid-Holocene climatic optimum, the Roman Warm Period, and the Medieval Warm Period, and the Recent Warming, as well as abrupt and short-lasting cold events (the 9.5-ka, 8.2-ka, 6.6-ka, and 3.4-ka events and the Little Ice Age)—have been well documented by proxy data. It has been suggested that most of these have been associated with significant hydrological

regime changes. Apart from some hemispherical consistent long-term climatic trends like the climatic optimum of the Mid-Holocene, or the generally cooling climate for the last 4 ka, evidence from empirical data and modeling document an extraordinary degree of spatiotemporal hydroclimate variability during most of the Holocene. Such spatiotemporal variability is normally associated with regional shifts in air mass patterns, rain belts, and moisture availability, over both land and sea (Maslin, Stickley, and Ettwein 2001). Therefore, in order to comprehend the Holocene climate variability of a given region, the emerging picture must be integrated within much broader scenarios. The advance in the study of Holocene climate has been facilitated by the wide applications of a range of dating methods (radiocarbon especially), as well as the availability of records and instrumental data that allow for high-resolution multiproxy research. Reconstructions show that when compared to the climatic manifestations of the Last Glacial Cycle, the Holocene climate changes appear moderate; these were nonetheless significant variations that at times played a crucial role in the waning and waxing of ancient groups, especially those that relied heavily on hydroclimate parameters, such as precipitation variability for agriculture-oriented societies.

This renders the Holocene a period of significant natural climatic oscillations that in turn would have been closely linked to the development, both culturally and technologically, of our society—from the momentous shift to farming and land-use changes, to the current large-scale industrialization and anthropogenically altered condition we see today—a period that has aptly been called the Anthropocene.

SEE ALSO: Optically Stimulated Luminescence

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Cosmogenic Dating

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Cosmogenic nuclides are defined as isotopes produced by any interaction between primary or secondary cosmic rays and matter (Gosse and Klein 2014). In contrast to the products of interactions taking place in the atmosphere (i.e., atmospheric cosmogenic nuclides such as ^{14}C), those resulting from interactions between the secondary cosmic ray flux and the atomic nuclei of minerals are named terrestrial (or in situ-produced) cosmogenic nuclides (TCNs). Among the secondary cosmic ray shower, the particles involved in TCN production at the (sub-) surface of the Earth's crust mostly are neutrons and muons (see COSMIC-RAY MUON TOMOGRAPHY). Highly energetic neutrons ($>30\text{ MeV}$) and epithermal (0.5 eV to 0.1 MeV)/thermal ($<0.025\text{ eV}$) neutrons induce TCN production through spallation and neutron capture processes, respectively. Muonic interactions imply both slow negative muons and fast muons. Whereas spallation is the prevailing production pathway within the uppermost 3–4 m of the lithosphere, the muonic contribution becomes dominant at depths greater than 3–4 m. Many nuclide species are generated from these interactions, but in order to be functional for dating purposes, they must fulfil a series of criteria (Dunai 2010; Gosse and Klein 2014), thereby limiting to six the number of TCNs commonly used as geochronometers so far. These nuclides are either stable gases (^3He , ^{21}Ne) or radioactive (^{10}Be , ^{14}C , ^{26}Al , and ^{36}Cl). Whereas quartz is the main target mineral of four of these (^{10}Be , in situ ^{14}C by contrast to atmospheric ^{14}C , ^{21}Ne , ^{26}Al), ^3He is mainly produced in olivine and pyroxene, and ^{36}Cl in calcite and feldspar.

Dating methods based on concentration measurements of in situ-produced cosmogenic nuclides yield numerical “uncalibrated” ages (Gosse and Klein 2014). They have considerably evolved over the last three decades, thanks to both

major technical and theoretical advances. On the one hand, progress in isotope mass spectrometry has allowed high-precision measurement of very low TCN concentrations in rock or sediment samples. In particular, high-energy accelerator mass spectrometers (AMS; see MASS SPECTROMETRY (MS)) developed in the 1980s can achieve extremely high discrimination against molecular and atomic interferences (Dunai 2010). On the other hand, a considerable and long-lasting effort of the community has resulted in progressive improvement of the knowledge of production rates, data processing, procedures of geochemical extraction and sampling approaches (Gosse and Klein 2014).

Depending on the aim of the study and/or the studied setting, concentration measurements of terrestrial cosmogenic nuclides allow assessment either of the duration of exposure to cosmic rays, or the duration of shielding from these. In the first case, the measured concentration of nuclide(s) is proportional to the duration of continuous exposure of surficial rocks or sediments to cosmic rays. The resulting geochronological tool relying on continuous nuclide accumulation is named *surface exposure dating*. In the second case, formerly exposed rock or sediments become permanently—or temporarily—protected from cosmic rays, implying a complete—or discontinuous—cessation of TCN production. The resulting geochronological tool relying on the differential decay of cosmogenic radionuclides is named *burial dating*. Both dating approaches are presented in this entry, but it must be borne in mind that their use is underpinned by several basic assumptions and limited by some intrinsic constraints. Consequently, distinct sources of uncertainties may affect or even bias the dating results. They fall into three broad categories: methodological (i.e., determination of site-specific production rate), observational/analytical (i.e., elevation of sampling site, sample preparation), and geological/geomorphological uncertainties (i.e., limited knowledge of the exposure history of individual samples) (Dunai 2010).

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Surface exposure dating

In the framework of a single exposure episode to cosmic rays, the total concentration of cosmogenic radionuclides (C_{tot}) in any geological or geomorphological surface in a *non-eroding* environment can be expressed as:

$$C_{\text{tot}}(t, x) = \sum_i \frac{P_i(x)}{\lambda} (1 - e^{-t\lambda}) + C_{\text{inh}}(x) e^{-t\lambda} \quad (1)$$

where t is the exposure time (i.e., the “age”), x is the subsurface depth, P the production rate of the radionuclide, i (subscript) the different production pathways according to the secondary particles involved in the production of the considered radionuclide (see above), λ the decay constant proper to the radionuclide, and C_{inh} the nuclide inventory already accumulated before the onset of the exposure episode of interest (the so-called inheritance, see below). The knowledge of two variables is thus fundamentally required to compute exposure ages: the amount of cosmogenic nuclides in the sampled material measured in the AMS, and the site-specific nuclide production rate. As for the second one, its determination must incorporate both the selection of suitable scaling factors and a potential shielding to cosmic rays at the sampling site (i.e., self-shielding due to the geometry of the sampling material itself, and/or shielding caused by the neighboring topography). The application time-span of surface exposure dating is highly variable and depends on the employed nuclide(s) and the environment where the method is applied. It ranges from historical times (e.g., Little Ice Age moraines; Schimmelpfennig et al. 2012) to the whole Quaternary and the Neogene under specific circumstances.

However, geological/geomorphological surfaces do not generally remain pristine over the time-span during which they are exposed to cosmic rays. A series of processes may act on these and consequently modify their cosmogenic inventory, which is essentially accumulated at the surface and within the few meters below it. Uncertainties induced by these processes, if not considered, may strongly bias the “true” exposure age of the landform (or the event that has to be dated). These processes may affect exposure ages in two contradictory ways. On the one hand,

processes involving either a loss of matter, such as erosion, weathering, surface lowering (e.g., wind deflation, illuviation), or subsequent mass shielding of the surface, such as loess, volcanic ash, or hillslope material, may substantially lessen the cosmogenic inventory in the sample. This may cause significant age underestimations. Since erosion is disregarded in Equation 1, the latter is unsuitable to compute exposure ages in eroding settings. Assuming a steady erosion rate through time, a correction factor might be used, provided that erosion—or more generally any loss of matter—can be separately evaluated (Dunai 2010). Otherwise, only *minimum exposure ages* can be provided from surface samples. On the other hand, any nuclide inventory already present in rocks or sediments before the exposure episode of interest may cause significant overestimations of real exposure durations. This process is known as inheritance (see Equation 1). In the case of sediments, pre-exposure may occur when the studied material is exhumed from bedrock and transported or temporally stored at the (sub-)surface on the hillslopes and in the drainage network (Anderson, Repka, and Dick 1996). Several approaches may help to overcome these limitations, such as the depth profile dating method, which consists of sampling sediments at regular depth intervals. Taking advantage of the neutron-dominated production (spallation) near the surface and the muon-dominated production at greater depths, it allows a simultaneous assessment of the exposure time, the post-depositional erosion rate, and the inherited component (Rixhon et al. 2014).

Over the last two decades, many fields of the geosciences have greatly benefited from the increasing use of surface exposure dating. The most common application aims to constrain the timing of deglaciation through the dating of glacial landforms, such as boulders lying atop of moraines and/or glacially polished bedrock (e.g., Schimmelpfennig et al. 2012). In addition, a wide variety of both erosional and depositional landforms have been successfully dated; they include alluvial fans, bedrock fault scarps, fluvial terraces (both bedrock strata and alluvial fills), landslide or rockfall scarp faces, lava flows, marine terraces (both wave-cut platforms and abandoned beach levels) and wind-polished bedrock. In archaeological settings, surface exposure dating has been

or can be theoretically applied to anthropogenic structures such as human-flattened rock outcrops, ancient stone buildings, or quarry walls. TCN dating of river sediments associated with lithic industries and/or paleofauna remains represents an insightful alternative (e.g., Rixhon et al. 2014).

Burial dating

Based on the differential radioactive decay of two cosmogenic radionuclides, burial dating determines “how much time the concentrations of both nuclides have decayed”. As a function of the corresponding half-lives (λ_A and λ_B), the pre-burial ratio $[R_{A/B}(0)]$ in the same sample decreases with increasing burial duration (t_b). This can be expressed as (Dunai 2010):

$$R_{AB}(t_b) = \frac{C_A(t_b)}{C_B(t_b)} = R_{AB}(0) e^{-t_b(\lambda_A - \lambda_B)} \quad (2)$$

where the concentrations $C_A(t_b)$ and $C_B(t_b)$ represent measured concentration values in the AMS and $R_{AB}(t_b)$ denotes their ratio. ^{26}Al and ^{10}Be represent the most common nuclide pairs for burial dating, although other nuclide combinations can be implemented (e.g., ^{26}Al – ^{10}Be – ^{21}Ne). While both nuclides are produced in the same mineral (i.e., quartz), the $^{26}\text{Al}/^{10}\text{Be}$ production ratio does not depend on latitude and altitude and only slightly changes with depth. As for the ^{26}Al – ^{10}Be pair, the application time-span of burial dating firstly depends on the analytical precision of ^{26}Al measurements in the AMS and on its half-life. In practice, it ranges from the Middle Pleistocene to the beginning of the Pliocene.

In contrast to surface exposure dating, burial dating of buried sediments is virtually unaffected by eroding or weathering agents at the surface, although this method has several intrinsic limitations too. Two prerequisites must be fulfilled to use Equation 2 to calculate burial ages. Firstly, the time-span during which incomplete shielding of the sediments occurs must be much shorter than the duration of subsequent burial (= fast burial). Secondly, sediments must be continuously buried by a ≥ 30 m thick overburden in order to prevent any substantial production via muons, which occurs at shallower depths (= complete and permanent burial). However, the second condition

is not fully met in many instances, implying an incomplete shielding to cosmic rays of buried sediments. In that case, Equation 2 is no longer valid because TCN production takes place after the burial event and may substantially contribute to the cosmogenic inventory (see Granger 2014). While this postburial production may therefore bias the computation of burial ages, one must verify whether the burial event has occurred at a constant depth or at time-dependent depth. Involving the collection of multiple samples in the buried sediment or rock, the isochron method overcomes the problematic postburial production and allows dating at shallower burial depths (Balco and Rovey 2008). This method relies on the fact that the ^{10}Be and ^{26}Al concentrations are different in each sample (i.e., distinct preburial histories) but that the $^{26}\text{Al}/^{10}\text{Be}$ ratio is identical.

Sediments in caves, especially in cave-deposited alluvium, represent the most common application of burial dating, for which both basic prerequisites are regularly met (Dunai 2010). Isochron burial dating has been successfully applied so far to paleosoils buried in till and fluvial terrace sediments (Balco and Rovey 2008). Burial dating applied to cave sediments or thick fluvial sequences associated with human remains and/or lithic industries (i.e., in case of buried quartz-bearing artifacts, they can be directly dated; e.g., Pappu et al. 2011) provides meaningful new insights into archaeological and paleoanthropological issues.

SEE ALSO: Dating (Burnt) Lithics; Radiation Exposure and Dating; River Systems

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Dating (Burnt) Lithics

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Introduction

Lithics, in particular those found in paleolithic sites, can be dated using luminescence dating methods.

Background

In the 1950s, Daniels and colleagues in the United States and Houtermans and Stauffer in Switzerland were the first to suggest that doses recorded by minerals could be determined using the luminescence emitted by these materials, and to define the bases of the thermoluminescence (TL) dating method (Aitken 1985). The first applications of this method, performed in the 1960s at the University of Oxford, the United Kingdom, concerned potteries and fired clays only. Further developments for dating burnt lithics came in the 1970s. The first problems that had to be overcome with lithics, compared to previous ceramic dating studies, concerned their preparation: Cutting slices of a stone fragment induced a complicated irradiation process with the artificial radioactive sources used in the laboratory, while grinding powder produced triboluminescence, an undesirable nondosimetric signal. This last problem was found to be avoidable with a simple chemical treatment of the prepared powder and this technique is still used nowadays. Methodological improvements in the 1980s allowed the application of TL dating of burnt lithics to a wide series of paleolithic sites, playing a non-negligible role in our understanding of the evolution of Neanderthals and modern humans.

For instance, in the Middle East, TL dating of burnt flints helped when discussing the filiation between Neanderthals and anatomically modern humans. In western Europe, the dating of burnt flints in various caves contributed to specifying the time range for the expansion of the Neanderthal lineage, from about 250 to 30 ka, the chronology of the different techno-complexes Neanderthal man was responsible for, and his late cohabitation with modern humans between ca. 40 and 30 ka. In North and South Africa, luminescence dating of burnt lithics helped to shed light on the cultural and behavioral evolution of anatomically modern humans. In particular, in North Africa, the Aterian culture, first believed to be younger than 60 ka, was found to have been for a longer duration, starting as early as 130 ka. In southern Africa, luminescence dating of burnt lithics suggested that early symbolic expressions, represented by engraved ochre fragments and engraved ostrich eggshells accompanying the Still Bay and Howiesons Poort techno-complexes, were much older (>60 ka) than the famous art expressions of the European Upper Paleolithic, post-dating 40 ka. Finally, the dating of burnt lithics was important for discussing the arrival of modern humans in the Americas before 20 ka, challenging the “Clovis first” paradigm, after which this continent was inhabited by humans only from 12 ka.

In most cases, luminescence dating of burnt lithics was used together with other dating methods, in particular optically stimulated luminescence (OSL) (see DATING AND OPTICALLY STIMULATED LUMINESCENCE) and infrared stimulated luminescence (IRSL) (see DATING AND INFRARED STIMULATED LUMINESCENCE), applied to sedimentary quartz and feldspar grains, respectively. In fact, since the late 1990s, most luminescence dating laboratories have focused on sediment dating and only a few currently continue working with burnt lithics. Meanwhile, comparisons of the different chronologies are highly valuable, as the methods differ in many points, thus allowing cross-checking.

An important methodological development since the turn of this century concerns the surface

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dating of rocks: In such a case, the target event is the last exposure of the rock surface to sunlight, for example, before it was inserted in a building. The rest of the discussion here will deal only with the dating of burnt lithics.

Physical basis of the method

As with the radiocarbon dating method, the physical phenomenon on which the luminescence dating method is based is radioactivity: Decays of radioelements occur with known, well-defined rhythms and constitute a natural clock. However, instead of measuring the remaining number of atoms, as is the case with the radiocarbon method, one exploits the radiative energy released during the decay by natural radioisotopes and absorbed by all the materials and then by the burnt lithics. Indeed, all sediments and rocks contain a small amount of uranium (^{235}U and ^{238}U series), thorium (^{232}Th series), and potassium (^{40}K) whose decay is slow enough to be considered as having been constant over the last hundreds of thousands of years. The amount of energy (or dose when the energy is based on the mass of material) absorbed by lithics thus depends primarily on the U, Th, and K contents and on the duration of the irradiation. Cosmic rays contribute to this dose. Therefore, the basic idea for luminescence and also electron spin resonance (ESR) (see DATING AND ELECTRON SPIN RESONANCE (ESR)) dating methods is to determine the total amount of dose absorbed by the sample from a starting point, on the one hand (equivalent dose in Gray (Gy)), and the rate at which the dose was absorbed (providing it was constant), on the other hand (dose rate in Gy/ka). The ratio of the equivalent dose to the dose rate gives the duration of the irradiation, and therefore the age being sought.

These methods are usually called paleodosimetric methods and they differ mainly with regard to the material studied, the zeroing event, and in the way the equivalent dose is determined. In the case of burnt lithics, the zeroing event is the last heating, for example, in an ancient hearth or under lava flows, and the luminescence properties are exploited to determine the

equivalent dose. Indeed, once a stone artifact is heated at high temperature (e.g., 500 °C), the memory of previous natural irradiations is lost. However, after subsequent irradiation (i.e., during its burial in the sediments) and under thermal (TL) or optical (OSL) stimulation, there is an emission of light whose intensity is related to the amount of radiative energy received since the last zeroing. This property is related to the discrete energy levels that charges (electrons and holes) can populate in crystals (band models) (see OPTICALLY STIMULATED LUMINESCENCE and THERMOLUMINESCENCE).

The precision of the method is about 10 percent at 1σ (68% confidence). The main limitation for the accuracy is that the assumption concerning the stability of the dose rate is not always true: Eventual changes in water content and transport of radioisotopes cannot easily be detected and taken into account.

The lithics on which luminescence dating is applied are mainly flints, cherts, quartzites, silcretes, vein quartz, and chalcedony.

Sampling

While getting a lithic in hand from an excavation and bringing it back to the laboratory does not present any particular difficulty a priori, several points related to the equivalent dose and dose rate determinations must be carefully taken into account in the field. In particular, it should be remembered that the luminescence signal must have been fully reset before burial. For flints and cherts, marks on their surface like cracks, cups, and reddening are typical of past heating. For quartzites and silcretes, the visual inspection is less informative and sampling is rather based on the location (e.g., a stone discovered in or close to a hearth). Further tests must be conducted in the laboratory in order to check that the past zeroing was sufficient to erase all the dose accumulated by the crystal before the event we seek to date. Even though most stone samples look opaque, it has been demonstrated that long exposure to sunlight can evict electrons from traps and then induce a bleaching of the luminescence signal down to 1 cm depth. It is therefore recommended

that the lithics that might be of interest for luminescence dating are protected from light once uncovered.

The dose rate is composed of two distinct parts: (1) the “internal” part, due to alpha and beta particles whose travel ranges in siliceous materials are 20 μm and 2 mm, respectively, and which originate from the sample itself (the beta and alpha dose coming from the surrounding sediment is usually neglected when the outer 2 mm of the stone is removed by sawing); (2) and the “external” part, due to cosmic rays and gamma rays. While the former can go across several meters of rocks, the latter have a travel range limited to about 30 cm. As a consequence, most of the external dose usually originates from a sphere centered on the lithics and having a 30-cm radius. However, because of the excavation, this virtual sphere is often destroyed, and therefore the gamma dose rate must be estimated from the closest stratigraphic profiles. Nevertheless, since the gamma dose rate can be spatially variable, it is recommended that the selected stones be as close as possible to a section whose radioactivity is representative of what the lithics experienced during their burial.

Preparation

Preparation of lithic artifacts includes mechanical and chemical treatments. All are done under subdued red-light which does not significantly affect the luminescence signals. First, the stone is sawed so that the outer 2 mm is discarded, as previously mentioned. The core is then crushed in order to obtain a powder that can be easily manipulated and irradiated (e.g., around 100 μm) (Figure 1). The powder is treated with hydrochloric acid to remove carbonates and avoid triboluminescence, and oxygen peroxide to remove eventual organic material. H_2SiF_6 is also sometimes useful for removing eventual feldspar grains. The powder is then rinsed, dried, and mounted on small discs or cups and loaded in the luminescence reader.

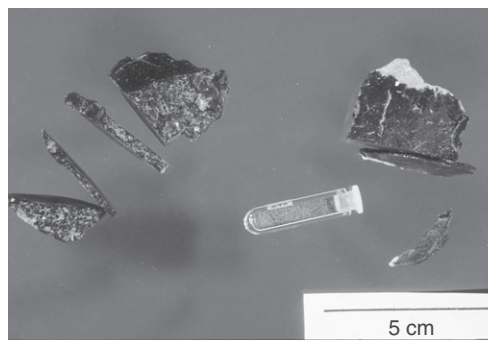


Figure 1 Different stages of sample preparation: sawed, then crushed into a fine powder.

Source: Photo courtesy of H. Valladas.

Equivalent dose

A variety of protocols can be applied in order to estimate the equivalent dose of burnt lithics, depending on the material (e.g., quartzites and silcrete versus flints and cherts), the signal (TL, isothermal TL, OSL; ESR has also been attempted), the wavelength chosen for detecting the luminescence signal, and the number of aliquots (multi-aliquots versus single aliquots).

For both flints and quartzites, the most widely used protocol exploits the TL signal and multi-aliquots (Valladas 1992). It requires the measurement of two series of TL signals detected in the blue emission band (Figure 2). For the first one, a series of known (beta or gamma) doses is given to aliquots from a natural sample and the measurement of their TL signals allows the building of an “additive” growth curve. The intercept of this curve on the x-axis gives an estimate of the equivalent dose (D). Meanwhile, the TL signal grows more slowly at low doses than at higher doses (supralinearity), so a correction must be done. The second series of measurements is made after the natural signal is erased (thanks to heat: for instance, 90 min at 350 °C) and a series of known (beta or gamma) doses are given. The extrapolation of the “regenerative growth curve” to the x-axis gives the supralinearity correction (Δ). The equivalent dose is calculated as the sum of D and Δ . Alternatively, the additive growth curve can be slid on the regenerative growth curve so

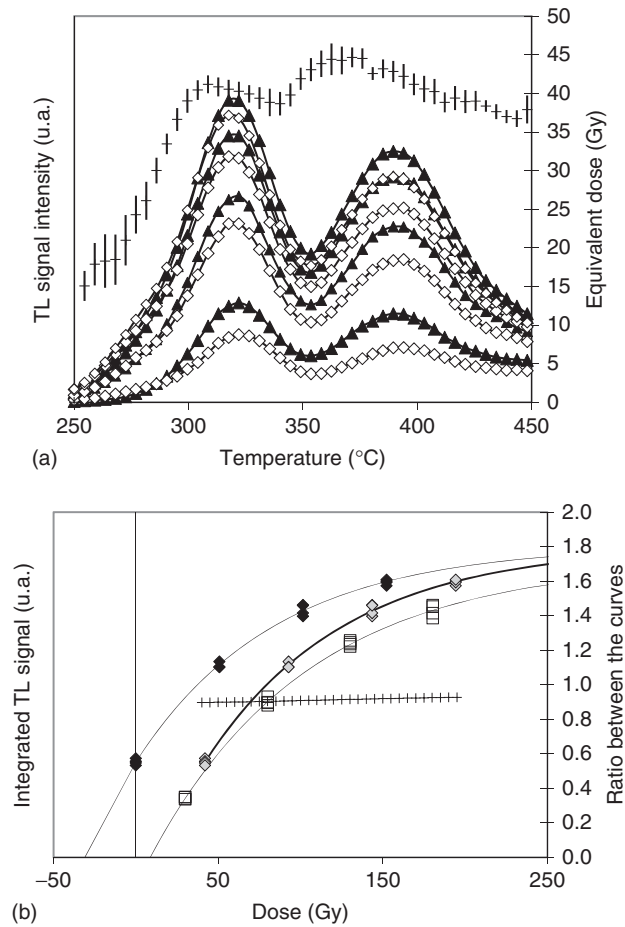


Figure 2 TL glow (a) and growth curves (b) for a quartzite sample. (a) TL glow curves for known doses added to the natural dose (black triangles) and doses added after zeroing (white diamonds); the dashed line with error bars represent D_e calculated when signals are integrated on 5 °C intervals (plateau test). (b) Additive (black diamonds) and regenerative growth curves (white squares); gray diamonds represent the additive growth curve after the slide toward the regenerative growth curve has been optimized. The dashed line with error bars represents ratios between the slide curve and regenerative curve.

that the ratio between the two growth curves is minimized (slide or normalization method): in that case, the slide length equals the equivalent dose.

A plateau test is used in order to check the validity of the equivalent dose: The equivalent dose is calculated following one of the two methods mentioned above as a function of the heating temperature. In case the geological dose (absorbed before the event to be dated) was not fully reset, the equivalent dose rises with

the temperature, whereas with a proper resetting, the equivalent dose is independent on the temperature (on most of the whole stable TL peak).

Some attempts were made to develop single-aliquot protocols, which have the advantage of requiring less material (allowing the dating of smaller samples) and permitting replication of the equivalent dose estimates. Such protocols, in particular the so-called single-aliquot and regenerative (SAR) dose protocol, are routinely used in the OSL dating of quartz grains extracted

from sediments. Some researchers studied the possibilities of exploiting the OSL signal in flints. However, they noticed that only some of them had a significant OSL signal and the method could not be generalized. Others used the orange-red TL signal in their single-aliquot approach. They suggested that the sensitivity (amount of light per unit of dose) of flints, measured in the orange-red waveband, was not changing much during the TL measurement, contrary to the most widely used blue TL signal. A short SAR protocol was proposed, but this did not seem to be efficient for most samples and cannot be used routinely.

For quartzites and silcretes, researches were also conducted to develop single-aliquot protocols, using the blue isothermal TL signal or OSL signals. In this last case, it seems that standard SAR protocols can be applied, providing that the samples were protected from light after they were uncovered. However, using the TL signal gives more direct information about the zeroing by heat (plateau test) before burial and this method remains the one that is preferred.

Dose rate

Methods for estimating the cosmic and gamma dose rate do not differ from those used for dating sediments and ceramics: Cosmic dose rate is calculated from the geographical coordinates, elevation, and burial depth. For the gamma dose rate, the measurements are done in the nearby sections, as previously mentioned. This can be performed with either a gamma field spectrometer or various types of dosimeters. They are inserted in the layers where the samples come from, at a depth of 30 cm, from a few minutes for the field gamma spectrometers, up to several months for the dosimeters.

It is also possible to reconstruct the gamma dose rate from the U, Th, and K measurements of the different constituents of the 30-cm-radius sphere around the sample. However, this might require a lot of work in complex sediments since the whole geometry must be recorded in the field, and samples representative of each constituent must be taken during the excavation and analyzed to determine their U, Th, and K contents.

Differences among lithics and ceramics and sediments are mainly due to the internal (beta and alpha) dose rate: Contrary to these last mentioned materials, the powder on which the equivalent dose is measured for lithics is not always made of well-defined grains extracted from the sample, but of aggregates of grains that were cemented (silicified) within the stone. It is thus not possible to get rid of the alpha dose rate by etching the powder with hydrofluoric acid, as is usually done with sedimentary quartz grains. The sensitivity to alpha particles (i.e., the amount of luminescence per given dose) is much lower than the sensitivity to beta, gamma, and cosmic rays. While it is not very variable in quartz grains (and so in quartzites, silcretes, etc.), it varies much more in flints and must be systematically determined for each sample.

The U, Th, and K contents in the lithics are measured on a portion of powder extracted during the sample preparation. Different methods can be used, such as high-resolution gamma spectrometry, inductively coupled plasma mass spectrometry (ICPMS), or neutron activation. Then, the distribution of the radioisotopes within the stone must be discussed. In flints and cherts, because of their cryptocrystalline structure (Figure 3a), it is usually assumed that the radioisotopes are distributed homogeneously. Therefore, all the emitted dose is absorbed by the crystals; that is, no attenuation factors are needed for calculating the dose rate. In quartzites and silcretes, the radioisotopes can, in most cases, also be assumed to be homogeneously distributed outside the quartz grains. Meanwhile, these grains are much larger than in flints (Figure 3b). For the beta dose, the typical sizes and the distances between grains imply, as in flint, that all the emitted dose is absorbed in the quartz grains, and again, no attenuation factors are needed. However, the grain size being as large as or larger than the alpha travel range, attenuation factors must be taken into account for calculating the alpha dose rate. Thin sections may be useful to determine the mean grain size within the sample.

The hypothesis of a homogeneous distribution is not always true, however. For example, some of the radioisotopes can be concentrated in some minerals (like zircons, very rich in U), present in low numbers in the lithic material, or along cracks. In that case, the emitted rays and particles

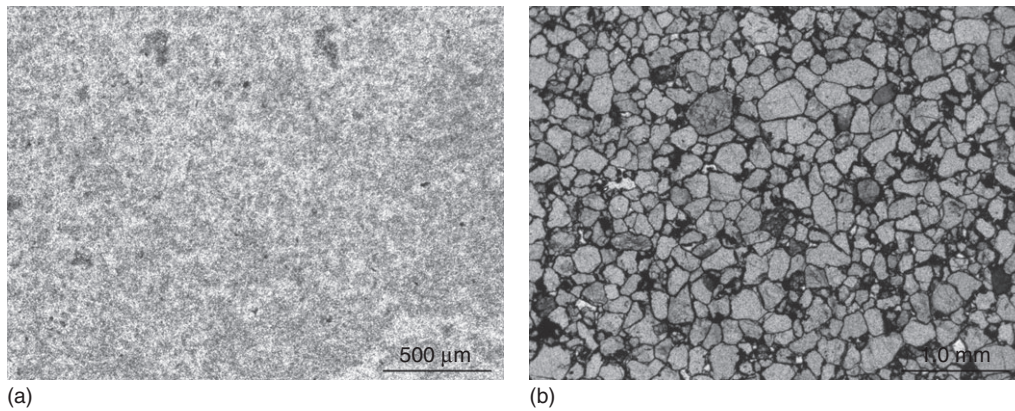


Figure 3 Thin sections of (a) a flint sample and (b) a quartzite sample. Both pictures were taken with natural light.

will not reach the luminescent crystals and the dose rate, if calculated assuming a homogeneous distribution, will be overestimated. Hence, it has already been noted that flint presenting very high U, Th, and K contents led to age underestimates.

Advantages and drawbacks of dating lithics compared to dating sediments

As mentioned earlier, most luminescence laboratories have experience in sediment dating, while only a few currently date burnt lithics. The reasons might be several. Suitable lithic artifacts are more difficult to find than quartz or feldspar grains, which are in the surrounding sediment. Because of the distance between the sample and the measurement points, the determination of the gamma dose rate requires many more measurements than for sediment dating in order to estimate the spatial variability and ensure that a representative estimate is obtained. The alpha sensitivity must be determined for each sample (which implies that the laboratory is equipped with a calibrated alpha source).

However, the dating of lithics presents several advantages over the dating of sediments. It is more directly related to human activity since the dated event is in most cases the heating in a hearth. The TL signal has a higher saturation rate than the (quartz) OSL signal, so that older samples can theoretically be dated. And last but not least, the beta and alpha dose rates are less prone to environmental changes (changes in water circulation, transport of soluble radioisotopes implying unstable dose rate, and so on) in lithics than in sediments.

SEE ALSO: Dating Ceramics and Luminescence; Dating in Archaeology

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Dating and Electron Spin Resonance (ESR)

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Introduction

Since the late 1940s and the development of the radiocarbon (C-14) method, a large number of very diverse numerical dating techniques have been developed in order to address the increasing need for robust chronological data in archaeology. There is indeed no ideal method that can provide accurate age results on any kind of sample, in any sedimentary context, and for any chronology. In contrast, by definition the use of a dating method, even the most established ones like C-14, uranium-series (U-series) (see URANIUM-SERIES) and argon-argon (Ar-Ar) (see ARGON-ARGON DATING), is limited by a range of intrinsic constraints and based on some implicit assumptions. As a consequence, sometimes these methods simply cannot be used at a given archaeological locality. For these reasons, the development and use of other geochronological tools, perhaps less popular and less standardized, such as electron spin resonance (ESR, also sometimes known as electron paramagnetic resonance (EPR)), luminescence (see DATING AND INFRARED STIMULATED LUMINESCENCE; DATING AND OPTICALLY STIMULATED LUMINESCENCE; and DATING CERAMICS AND LUMINESCENCE), and terrestrial cosmogenic nuclides (TCN) dating (see COSMOGENIC DATING), is essential. The ESR phenomenon was described by E. Zavoisky in the mid-1940s and first used as a dating tool a few decades later (Ikeya 1975). Since then, the technique has been tested and developed on a wide range of materials, including phosphates, carbonates, and silicates (an overview may be found in Ikeya 1993). Although less well known than other numerical dating methods, ESR has nevertheless become a landmark in Quaternary geochronology over recent decades, and was

demonstrably found to be especially useful for Paleolithic sites beyond the radiocarbon time range (ca. 50 ka) and/or located in nonvolcanic areas.

Basic principles

ESR is a radiation exposure (or paleodosimetric) dating method based on evaluation of the effects of natural radioactivity on materials over geological times, similar to methods centered on luminescence phenomena. These effects are quantified in terms of radiation dose—that is, the amount of energy absorbed by a given material due to its exposition to radiations originating from natural radioactivity. At a microscopic level, this interaction creates unpaired electrons that are trapped in the crystal lattice of a material. They give rise to an ESR signal whose intensity is directly proportional to the number of trapped charges, and thus to the amount of radiation dose absorbed by the sample over time. The magnitude of this dose is directly dependent on the intensity of the natural radioactivity present in the sample and its surroundings, and duration of the exposition (Ikeya 1993). The basic ESR age equation may be expressed as follows:

$$D_E = \int_0^T D(t) dt \quad (1)$$

where D_E is the equivalent dose (in Gray (Gy)), which is an estimate of the paleodose—that is, the total dose absorbed by the sample during the time elapsed between the zeroing of the ESR clock ($t = 0$) and the sampling (today (T), $t = T$)—and $D(t)$ is the dose rate (usually in Gy/ka or $\mu\text{Gy/a}$), or annual dose, which is the average dose absorbed by the sample in one year. In many cases, the dose rate is constant over time, and the equation may then be simplified as follow:

$$T = \frac{D_E}{D} \quad (2)$$

where T is the ESR age of the sample—that is, the time of exposure of the sample to natural

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radioactivity since the ESR signal has been last reset to 0.

Analytical procedure: a brief overview

To make it simple, the ESR dating analytical procedure consists of the determination of the two main parameters D_E and D . On the one hand, D_E is obtained using ESR spectroscopy, by artificially aging the samples at increasing irradiation doses in order to describe the behavior of the studied signal. A dose response curve showing the ESR intensity versus the dose is obtained, which enables determination of the dose absorbed by the material between $t = 0$ and T (today). On the other hand, the dose rate is obtained from evaluation of the amount of radioactivity within the sample and its surroundings, through a combination of in-situ and laboratory measurements using a wide range of different analytical techniques. The value is then attenuated according to different correction factors related to the material's density, geometry, and thickness, or water content. Further details about the analytical procedure may be found in Duval (2017).

Main dating applications

The first ESR dating study by Ikeya (1975) was performed on speleothems, but nowadays the most popular ESR applications in archaeological contexts are undoubtedly on optically bleached quartz grains extracted from sediment and fossil tooth enamel.

Because quartz is one of the most abundant minerals on the earth's surface, it is naturally present in many of sedimentary contexts that frequently document archaeological evidence (e.g., cave infillings and fluvio-lacustrine deposits). Similar to optically stimulated luminescence (OSL) dating, ESR dating of sedimentary quartz is based on the study of light-sensitive signals whose intensity is reset under sunlight exposure. This phenomenon is called optical bleaching and mostly occurs during sediment transport. Once the sediment is buried, and thus sheltered from sunlight, the ESR signal measured in those quartz samples increases as a result of their interaction with radiations from natural radioactivity.

Specific details about this application may be found in a review by Tissoux (2015). In particular, recent development of the multiple centre approach in the early 2000s has contributed to increasing the reliability of the ESR age results produced, by enabling better constraint of the inherent uncertainty related to the potential incomplete bleaching of the ESR signal during sediment transport.

After the first dating attempts performed in the early 1980s on fossil bones, studies were rapidly focused on fossil teeth instead, because these are usually better preserved in archaeological sites and less sensitive to diagenetic processes that could alter their structure and reset, partially or totally, their ESR signal. Tooth enamel is known to be an excellent dosimeter, that is, a material able to register a dose from a few milliGray to several thousands of Grays. However, the dose rate evaluation is made quite complex due to the fact that dental tissues are known to behave as open systems for U-series elements. In other words, unlike speleothems, for example, teeth frequently experience delayed uranium uptake after the death of the organism. As a consequence, the kinetics of the incorporation of uranium into each dental tissue should be modeled by using the U-series data collected for each dental tissue in combination with ESR dose evaluation. This is called the combined U-series/ESR dating approach. Further details regarding the ESR dating application to fossil teeth may be found in a review by Duval (2015). In particular, recent development of a semi-nondestructive procedure causing minimum damage to the teeth has opened the possibility to date highly valuable samples like hominin fossil teeth whose age lies beyond the radiocarbon time range.

An overview of recent methodological developments and a discussion about the current challenges faced in ESR dating of fossil teeth and quartz grains may be found in Rixhon et al. (2017). Additionally, many other materials have been tentatively dated in archaeological contexts, including geological apatite, corals, mollusc shells, snails, and burnt flints. A nonexhaustive overview is provided in Table 1.

Table 1 Examples of ESR dating applications in archaeological context published since the 1990s (see references in Duval 2017 and Ikeya 1993 for earlier works).

<i>Material</i>	<i>Dated sample</i>	<i>Event (re)setting the clock to 0</i>	<i>Correlation with archaeological evidence</i>
Carbonate	Cave deposits (speleothem, stalagmite, flowstone)	Crystallization (formation of mineral)	Usually provides a minimum or maximum age constraint on hominin occupation found in a layer located below or above the carbonate formation
	Terrestrial mollusc shell or snail	Crystallization (formation of mineral)	If shells have been brought by hominins, or are found in association with archaeological evidence, they may be considered as coeval with hominin occupations. Note: Life time of the organism is usually considered to be negligible in comparison with the geological time elapsed since burial of the shell
Phosphate	ESR dating of fossil teeth	Crystallization (formation of mineral)	If mammal fossil teeth have been brought by hominins, or are found in association with archaeological evidence, they may be considered coeval with hominin occupations. Note: Life time of the organism is usually considered to be negligible in comparison with the geological time elapsed since burial of the tooth
	ESR dating of authigenic terrestrial apatite veins	Crystallization (formation of mineral)	Apatite is formed from diagenetic (i.e., post-depositional) processes within sedimentary deposits, and can therefore only provide a minimum possible age for any archaeological evidence found in the same layer
Silicate	Optically bleached quartz grains extracted from sediment	Optical bleaching	ESR provides a burial age for sediments that may contain archaeological evidence, and can be then considered coeval with hominin occupations, if no reworking is observed
	Heated quartz grains extracted from sediment	Heat	If the heat may be related to fire due to anthropic activity, the material dated by ESR can then be considered coeval with hominin occupations, if no reworking is observed
	Burnt quartz pebbles and flints	Heat	If the heat may be related to fire due to anthropic activity, the material dated by ESR can then be considered coeval with hominin occupations, if no reworking is observed
	Quartz grains extracted from pottery	Heat	Directly related to anthropic activity

Main pitfalls

By definition, the use of any dating method is limited by a range of intrinsic constraints and based on some implicit assumptions. Because these are very rarely openly stated, expectations regarding numerical dating methods from nongeochronologists are sometimes unrealistic. Consequently, it is worth recalling here that ESR can only work under the following conditions:

- Unlike many radiometric methods *sensu stricto* (e.g., C-14, U-series, Ar-Ar) for which only the sample to be dated is needed to produce a numerical age result, paleodosimetric methods such as OSL, thermoluminescence (TL), and ESR require additional information about the surrounding environment to ensure a correct dose rate evaluation. In other words, a sample out of context cannot be dated. This is usually not a problem with ESR dating of quartz, as sediment samples are collected in situ, but may sometimes be more complicated with fossil teeth. As teeth can be taken from collection, the exact original (geographical and stratigraphical) location sometimes may be unknown, or the layer/outcrop/site may no longer be accessible. In this case, some precautions should be taken during the excavation by collecting the sediment surrounding the tooth. Otherwise, the absence of this information may induce later on a non-negligible uncertainty on the dose rate evaluation, and thus on the final ESR age result.
- D_E represents an estimate of the total dose of radiations absorbed by the sample over geological time. This estimate may be more or less reliable depending on whether the sample has been affected by processes leading either to a partial or complete resetting of the ESR signal (e.g., dissolution/recrystallization, heat, optical bleaching, mechanical stress), or to the increase of the main radiation-induced ESR signal by additional exposure to a radioactive source (e.g., exposure of the tooth sample to X-rays during a computed micro-tomography (μ CT) scan analysis). This may happen not

only during the geological history of the sample, but also after collecting samples, prior to or during sample preparation.

- The dose rate is evaluated by measurement of the actual radioactivity of the sample and its surroundings, and under the assumption that current conditions are representative of past history: they are considered either to have been constant over time or to have evolved following a trend that can be accurately modeled. Otherwise, if not detected, any substantial modification of the sample or its surroundings by diagenetic processes (e.g., recent uranium mobilization, water circulation, sediment reworking, bioturbation) can potentially introduce a significant bias in dose rate evaluation and, thus, on calculated age.

ESR compared with other numerical dating methods

ESR age calculation involves many parameters in order to accurately estimate the different components of the dose rate: the number may exceed 20 depending on the characteristics (size, geometry, open/closed system) of the sample considered. Each parameter has an associated uncertainty that needs to be included and propagated into the final age calculation, which usually makes a final age error (usually quoted at a 1σ confidence level) in the range of 5–15 percent. For this reason, the precision achieved with ESR may somewhat contrast with that of other reference dating methods such as Ar-Ar, C-14, and U-series, which can be < 1 percent at 2σ . However, there are nevertheless many situations in which ESR may be especially useful in an archaeological context.

The selection of a dating method at a given archaeological site depends on many parameters, such as the sedimentary context, the archaeological and paleontological material found and its preservation, and the expected chronology. Radiocarbon dating is probably the most popular and standardized method, which undoubtedly makes it the preferred option to date a wide range of materials, including fossil remains, over the last 50 ka or so. Beyond this time range, ESR dating is among the best candidates to obtain direct

ages on fossil remains (e.g., Grün et al. 2010), whereas most of the numerical methods can only provide an indirect age based on the dating of the deposits directly or indirectly associated with archaeological evidence.

U-series analyses can provide high-resolution ages on fossil remains; however, these results should be regarded only as minimum estimates, as uranium uptake in dental tissue may be significantly delayed after death of the organism. Consequently, the true age of the fossil remains would be similar or older than the U-series age. In contrast, when combined with U-series, ESR can provide a burial age for fossil teeth. Previous dating applications have shown that it can produce reliable ages from a few 20–30 ka to more than 2 Ma. Since the mid-2000s, technological developments have opened the possibility to date highly valuable samples, such as human teeth, by causing minimal damage to fossil material. One of the best examples in that regard is the recent direct dating of *Homo naledi* using a semi-nondestructive approach (Dirks et al. 2017) based on the combination of ESR analyses of enamel fragments with high-resolution U-series analyses performed by laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS).

The first ESR dating application published by Ikeya (1975) showed promising results for speleothems. However, rapid development of the U-series (U-Th) dating method over the following decades has made it the best option to date carbonated formations of less than 500 ka in cave environments, as it offers faster and more accurate dating results on speleothems and other carbonated formations than ESR dating. For older deposits, the recently developed U-Pb dating method can take over as soon as the amount of uranium and lead present in the speleothems is sufficient. If not, then ESR may become an interesting alternative option, as it would make evaluation of the dose rate (and, in particular, alpha and beta dose rate components) more straightforward.

Given the wide range of materials that can be dated using ESR, the method can potentially be used in almost any Quaternary environment. This contrasts with most of the numerical dating methods, which are usually limited to a specific context. In particular, it was demonstrated to

be especially useful for Pleistocene archaeological sites beyond the radiocarbon time range and located in nonvolcanic environments (thus precluding use of the Ar-Ar method); such conditions are frequently found in Europe and northern Africa, and the number of methods that can be used in these contexts appears to be quite limited. Standard luminescence dating (mainly OSL) procedures have proven to be especially useful to date quartz and feldspar grains over the last approximately 200–300 ka in low-dose-rate environments, although it is worth mentioning that recent experimental developments have pushed the lower application limit of the method back to about 1 Ma. Because ESR signals in quartz show higher radiation saturation levels than luminescence signals, it is usually considered that ESR is better than standard OSL procedures in dating Early to Middle Pleistocene deposits (e.g., Cordier et al. 2012). Over this time range, the TCN dating method might also be applied unless conditions are not considered suitable (e.g., not enough quartz content in the sediment; limited sediment overburden).

Nowadays in Paleolithic archaeology, it has become standard procedure to combine different dating methods at a given site, in order to produce a more robust chronological framework. In other words, since the 2000s, ESR dating results have been increasingly compared with independent age control in a range of different environments. For example, both ESR on teeth and Ar-Ar dating methods provided consistent results at Guado San Nicola site (Italy) (Pereira et al. 2016). Similarly, OSL and ESR dating of quartz from fluvial deposits at the Middle Paleolithic site of Cuesta de la Bajada have produced close age estimates (Duval 2017). Other examples of successful multitechnique dating works involving direct ESR dating of hominin teeth have been documented at El Sidrón (Torres et al. 2010) and Rising Star (Dirks et al. 2017) caves. These few examples of comparative dating studies demonstrate the great potential of the ESR dating method in archaeological contexts.

To summarize, ESR appears to be a highly versatile dating method which can produce ages on fossil remains like C-14, on quartz grains like OSL and TCN methods, and on speleothems like U-series, which make it applicable in almost

any archaeological context over the last 2.6 Ma. Although the precision achieved is significantly lower than that of the more established methods, ESR is in many cases the only numerical method that can simply be used at a given site.

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Dating and Infrared Stimulated Luminescence

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Luminescence dating of silicate minerals is based on their capacity to store energy when exposed to ionizing radiation: a process which involves charge (i.e., electrons) becoming trapped at defect sites within the crystal lattice. This trapped charge can be released upon stimulation by heat, resulting in thermoluminescence (TL), or photons, which results in optically stimulated luminescence (OSL) (see DATING AND OPTICALLY STIMULATED LUMINESCENCE and DATING CERAMICS AND LUMINESCENCE). In IRSL dating, trapped charge is released via stimulation with wavelengths in the infrared (IR) portion of the spectrum (800–1000 nm).

Quartz and feldspars are the most commonly used minerals for luminescence dating of sedimentary deposits. Although OSL may refer to any signal involving stimulation using photons, the term is generally used in the literature to refer to luminescence dating of quartz grains using blue or green light stimulation. In contrast to quartz, which is not highly sensitive to IR stimulation, feldspars can have their trapped charge readily depleted by exposure to IR photons. Hence, IRSL dating of sediments almost always refers to dating of feldspar mineral grains.

IRSL dating utilizes light-sensitive electron traps to determine the last time feldspar grains were exposed to daylight (i.e., timing of sediment deposition). The technique may also be applied to feldspar grains that have had electron traps emptied via heating, such as in pottery, but the majority of archaeological geochronology studies have tended to employ IRSL as a direct sediment dating tool. In nature, feldspar grains

that undergo sedimentary transportation prior to burial are usually exposed to sufficient sunlight to completely reset or “bleach” any previously stored charge within light-sensitive traps. Once buried and shielded from light, this charge starts to accumulate again at a rate that is proportional to the background level of alpha, beta and gamma radiation arising from within the sedimentary environment, as well as radiation from cosmic rays. IRSL dating requires an estimation of the total trapped charge accumulated since burial, expressed as an equivalent dose (D_e) in units of grays (Gy), and the rate of ionizing radiation exposure during burial, or environmental dose rate (Gy per unit time). The former is estimated via IRSL measurements made on the feldspar grains being dated, while the latter is determined from radionuclide concentrations (i.e., K, U, and Th) in the sediment and within the grains, as well as contributions from cosmic rays. The IRSL age of a sample is then calculated by dividing the D_e by the environmental dose rate.

Huntley, Godfrey-Smith, and Thewalt (1985) first reported the use of light-sensitive electron traps for determining the last time quartz grains were exposed to daylight, as part of a study employing green light stimulation. The potential for using IRSL in geological dating applications was first proposed by Hütt, Jaek, and Tchonka (1988), who measured the excitation spectra of irradiated potassium feldspar samples. These initial dating discoveries were followed in the 1990s and 2000s by the rapid development of automated instrumentation using inexpensive stimulation sources (light-emitting diodes) and single-aliquot regenerative (SAR) measurement procedures (see also DATING AND OPTICALLY STIMULATED LUMINESCENCE), as well as advanced statistical age modeling. These efforts focused on optical dating of quartz and feldspar grains extracted from sediments, and have led to standardization and proliferation of IRSL and OSL dating research in archaeological contexts.

Feldspar IRSL signal characteristics and dating procedures

One of the main advantages of using feldspars for archaeological and geological dating is their abundance in sedimentary environments. Feldspars are aluminosilicates with tetrahedral structures comprising four oxygen atoms and a silicon atom. Cations, commonly potassium (K), sodium (Na) and calcium (Ca), are inserted into the lattice where aluminum atoms replace silicate atoms. Compositions made up solely of potassium, calcium and sodium cations form end-members in ternary diagrams of natural feldspar types. Intermediate feldspars have chemical compositions containing proportions of these cations, specifically K–Na proportions (alkali feldspars) and Na–Ca proportions (plagioclase feldspars).

Investigations into the luminescence emission spectra (i.e., the wavelength of emissions) of feldspars, carried out on both sedimentary samples and on well-characterized museum specimens, have shown that their emissions are not spectrally uniform across mineral polymorphs but vary according to their elemental composition (see Krbetschek et al. 1997 for an extensive review). In general, feldspar IRSL covers several spectral bands with emissions at ~730, ~560, ~430, ~330 and ~300 nm. Ultraviolet emissions in the 290–310 nm and 320–340 nm wavebands appear in all feldspar types but are more dominant in plagioclase or sodium-rich feldspars, with the 290–310 nm emissions being less stable. Violet–blue (390–440 nm) emissions are dominant in alkali feldspars and their intensity has been positively correlated with potassium content. Yellow–green (550–570 nm) IRSL emissions dominate in plagioclase feldspars, particularly albite (sodium end-member), although this signal is not commonly used for dating. Finally, TL measurements indicate that red to far-red emissions (600–750 nm) are present in most feldspar types.

In the past, IRSL dating of feldspars has been undertaken on both fine- and coarse-grained sediment fractions. Polymineral fine-grains (4–11 μm) have been extensively targeted for dating, with special interest in IRSL applications to loess and other silt-sized sediments devoid of

coarser grains. In these studies, D_e measurements are commonly made on aliquots composed of thousands of grains that have not been subjected to heavy liquid density separation. As a result, the measured IRSL signal can arise from feldspar mixtures of unknown mineralogical composition. The routine use of coarser (>63 μm) potassium feldspar grains for dating was first described in the 1980s and has since become a commonly used approach in archaeological applications. The extraction of coarse feldspar grains from bulk sediment samples is usually performed via heavy liquid separation of the <2.58 g/cm³ fractions. Dating using coarse grains of potassium feldspar has the advantage of allowing a firmer constraint on the internal dose rate calculation, since K content can be quantified more easily (see below), and it ensures that the signal being measured comes from a purer feldspar admixture. IRSL dating studies are generally carried out on commercially available readers fitted with IR (875 nm) stimulation sources. The detection systems typically involve a blue-sensitive photomultiplier tube and blue filter packs with the aim of measuring violet–blue emissions (peak transmittance at 420 nm), as well as avoiding inputs from less stable ultraviolet signals. Single-grain IRSL dating studies have also been undertaken using readers equipped with IR (830 nm) lasers designed to stimulate individual grains with a high degree of reproducibility.

Feldspars are often considered advantageous over quartz because of several superior luminescence characteristics. Although feldspar IRSL decay and bleaching rates are slower than those associated with the main (so-called fast) OSL quartz signal (complete signal resetting may take minutes instead of seconds), their signals are usually considerably brighter than quartz. Feldspar IRSL therefore provides a preferred alternative in situations where quartz OSL sensitivity is weak or unreliable (e.g., glacially-derived sediments), as well as where quartz is absent. Additionally, feldspar IRSL signals exhibit significantly higher dose saturation properties in comparison with quartz, and can adequately record administered doses in excess of 1000 Gy. In contrast, quartz OSL typically saturates at doses of 100–250 Gy (see also DATING AND OPTICALLY STIMULATED LUMINESCENCE). These higher dose saturation

limits are advantageous for dating older archaeological sediments that lie beyond the conventional range of quartz OSL techniques.

Another potentially favorable feature of potassium feldspar dating is that a large portion of the environmental dose rate is derived from within the grains themselves owing to their high ^{40}K and ^{87}Rb contents. On average, the concentrations of these internal elements amount to $\sim 12.5\%$ and $400\text{ }\mu\text{g/g}$, respectively, which means that the internal dose rate of a potassium feldspar sample can be comparable to its external dose rate in certain samples. A relatively large internal dose rate has the benefit of minimizing the effects of poorly constrained external dose rates, which can arise from beta microdosimetry variations, undetermined variations in long-term sediment water content, or disequilibrium in the decay chain of ^{238}U and ^{232}Th . This can be particularly useful for dating archaeological contexts in which the long-term external dose rate cannot be constrained with a high degree of confidence.

Anomalous fading and feldspar IRSL

Despite the aforementioned benefits, feldspar IRSL dating has been overlooked in the past due to a form of signal instability that can result in age underestimation. Since the initial work by Wintle (1973), it has been known that luminescence signals from feldspars suffer from “anomalous fading,” making them unreliable for dating without suitable age correction. This form of signal instability is termed “anomalous” because kinetic measurements of TL peak lifetimes indicate the signal should be stable over at least tens of millions of years. However, samples that have been stored following laboratory irradiation show an unexpected decrease in their luminescence signal by as much as 50% in a matter of days to weeks; with the decrease in signal following a logarithmic time decay function. This loss of trapped charge in an otherwise stable trap is due to tunneling of electrons during burial or storage (Spooner 1994). In sedimentary feldspar grains, IRSL signal fading rates measured at low temperatures (i.e., 50°C) are usually of the order of 2–10% per decade. Observed variations in these

values have been partly linked to the crystallization history of the mineral, where poorly ordered tetrahedral structures associated with rapid cooling (e.g., volcanic feldspars) may exhibit higher fading rates than well-ordered structures.

Attempts to circumvent anomalous fading have led researchers to investigate different types of IRSL signal in feldspars, such as red IRSL and red TL emissions. Others have investigated the relationship between feldspar type and anomalous fading using both museum specimens and sedimentary feldspar grains, with the aim of determining whether certain mineral compositions are less susceptible to the fading phenomenon and could thus be targeted for dating (e.g., Spooner 1994).

However, the most common approach for dealing with anomalous fading in IRSL dating is to correct the final ages using sample-specific fading assessments. A number of methods have been proposed for this purpose. Of these, the most widely applied is that presented by Huntley and Lamothe (2001), which is based on the tunneling probability of trapped electrons. This correction method is only applicable to the linear part of the dose response curve, and so it is used primarily on samples that are less than a few tens of thousands of years old. For older archaeological samples, conventional IRSL dating (i.e., measured at 50°C) can only provide minimum age constraints.

Recent advances—overcoming anomalous fading using pIR-IR

In recent years, a significantly more stable signal from feldspars has been discovered, and is now becoming increasingly used in archaeological dating applications (see Arnold et al. 2015 for review). This signal is obtained by first stimulating the sample with IR at low temperature (i.e., 50°C) and then performing a second IR stimulation at an elevated temperature, usually higher than 200°C . The second measured IR signal is commonly referred to as post-infrared IRSL (pIR-IR), and it has been shown to be substantially less affected by anomalous fading than conventional IRSL (Thomsen et al. 2008). A large compilation of more than 150

laboratory values published to date from geologically diverse regions has revealed a global average fading rate for the pIR-IR signal of 1–1.2%/decade (Arnold et al. 2015), which is a considerable improvement from those obtained from low-temperature IRSL measurements. Additionally, some studies have reported natural pIR-IR signals that intercept the saturated portion of the dose response curve, which has been interpreted as an indication that a non-fading signal is being measured by the pIR-IR procedure.

Since the discovery that the pIR-IR signal from feldspars is less affected by (or devoid of) anomalous fading, much attention has been focused on understanding the physical basis of the phenomenon. To date, the most accepted mechanism for explaining IRSL production is the band-tail state model of Poolton et al. (2002). In this model, excited electrons may undergo tunneling or recombine following photon-assisted band-tail hopping (Jain and Ankægaard 2011). Detailed studies of signal fading, recombination processes and excitation spectra, suggest that the production of IRSL and pIR-IR arise from the same trap (Jain and Ankægaard 2011; Thomsen et al. 2008). These studies suggest that the improved stability of the pIR-IR signal is due to differences in recombination probabilities in nearby and distant electron–hole pairs, where the former have higher rates of tunneling than the latter. The process may be described as follows: trapped electrons located further from a recombination site, and which have not undergone tunneling during burial, are excited to the band-tail states by the first IR stimulation and are allowed to deplete the localized (less stable) electron–hole pairs. The depletion of these localized electron–hole pairs increases the probability for the newly excited electrons (i.e., those that are de-trapped by the subsequent high temperature IR stimulation) to recombine at distant (more stable) electron–hole pairs, resulting in a renewed IRSL signal that is substantially less affected by fading.

pIR-IR dating of potassium-rich feldspar extracts is now rapidly becoming the method of choice for archaeological samples that are too old to be dated with quartz OSL, or for samples displaying unsuitable quartz OSL characteristics

(i.e., low sensitivity). A number of pIR-IR measurement protocols have been proposed, with the majority designed to determine replicate D_e values for individual subsamples (single aliquots) of a given sample. Most pIR-IR studies have used a two-step SAR D_e measurement procedure, in which an initial low-temperature IRSL measurement performed at 50 °C is followed by a second measurement at a higher temperature (either 225 °C or 290 °C, depending on sample suitability). The use of higher stimulation temperatures may also be driven by the need to isolate a more stable signal. Further variants of this protocol include making multi-elevated-temperature (MET) measurements on the same subsample at increasing stimulation temperatures to obtain a series of D_e estimates. In this protocol, the appearance of a D_e plateau at higher stimulation temperatures is indicative of significantly reduced or absent fading (see review by Arnold et al. 2015).

Although isolating a more stable pIR-IR signal by increasing stimulation temperature may be appropriate in some samples, it has also been shown that residual doses of tens of Gy may remain even after extensive bleaching times of several hours under sunlight or artificial illumination. Moreover, these pIR-IR residuals tend to become substantially larger as the pIR-IR stimulation temperature is increased. The effect of this hard-to-bleach component may be significant in younger samples (<10 ka), for which the natural accumulated dose is relatively small. In these cases, the presence of a pIR-IR residual may result in significant age overestimation. In older samples, this residual dose may play an unimportant role and is unlikely to affect the final age beyond the existing dating uncertainties (typically ~5% at 1σ). That said, it remains important to determine the presence and size of pIR-IR residual doses on a sample-by-sample basis—by performing sunlight bleaching experiments—in order to assess whether a correction is needed when calculating the final ages. Similarly, monitoring of anomalous fading should be performed routinely in pIR-IR (or IRSL) dating studies since sample variation is commonplace (Spooner 1994), and response to measurement conditions (i.e., pIR-IR stimulation temperature) may differ considerably (Arnold et al. 2015).

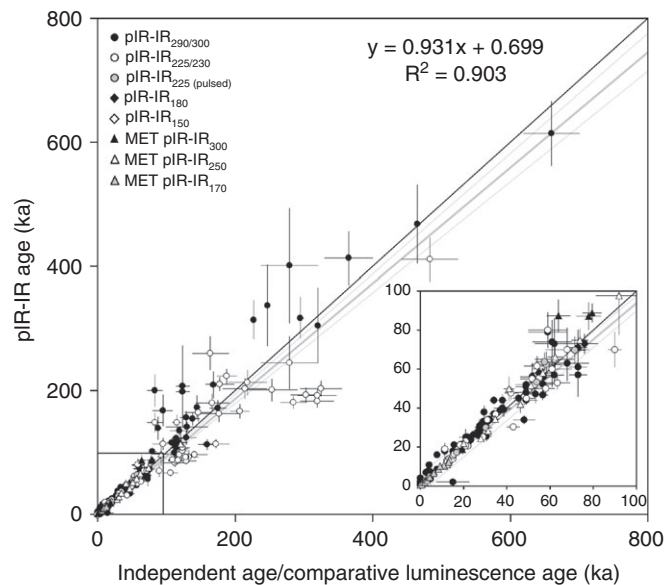


Figure 1 Comparison between post-infrared IRSL (pIR-IR) ages, obtained using different equivalent dose (D_e) measurement conditions, and known sample age derived independently or via alternative luminescence methods. Results include all published studies up to 2014. The thick black line denotes a 1:1 relationship, while the thick and thin gray lines denote the linear regression for the dataset and the confidence intervals at the 95.4% confidence level, respectively. Modified from Arnold et al. (2015).

Over the past eight years, a number of pIR-IR chronologies have been produced for independently dated sediment sequences spanning ages ranging from the present day to hundreds of thousands of years ago. The latest global review, which includes all known-age studies published up until 2014, show generally good correspondence between pIR-IR ages and independent age control for samples covering Late and Middle Pleistocene timescales (Figure 1). However, a certain amount of scatter is also apparent in this known-age dataset, indicating that individual pIR-IR measurement conditions are not universally applicable to all samples. Further known-age comparison studies are needed over the 250–800 ka time period to confirm the broader suitability of pIR-IR dating over early Middle Pleistocene timescales (Arnold et al. 2015).

Current feldspar dating research is focusing on single-grain pIR-IR dating protocols, particularly in archaeological settings. This approach has the potential to provide improved pIR-IR dating reliability in complex archaeological environments that may be subjected to limited daylight exposures or the influence of

post-depositional disturbances (e.g., caves and rock shelters).

SEE ALSO: Dating and Optically Stimulated Luminescence; Dating Ceramics and Luminescence

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Dating and Optically Stimulated Luminescence

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Overview and principles of OSL dating

Optically stimulated luminescence (OSL) dating is part of a family of trapped charge geochronology techniques that utilizes the ability of natural minerals to absorb and store energy from ionizing radiation exposure over geological timescales (see also DATING CERAMICS AND LUMINESCENCE and DATING AND ELECTRON SPIN RESONANCE (ESR)). Over the last few decades OSL has emerged as one of the most widely used methods for constraining the age of Late Pleistocene sedimentary deposits preserved at archaeological sites. The increased use of OSL in archaeological dating applications has been fueled by a number of important methodological developments, including the advent of single-grain techniques. The term OSL dating is often used interchangeably with optical dating, though the latter is better thought of as a broader term encompassing various luminescence dating signals produced by visible light stimulation (OSL and thermally transferred OSL (TT-OSL)) and exposure to near-infrared radiation (infrared stimulated luminescence (IRSL) and post-infrared IRSL (pIR-IR); see also DATING AND INFRARED STIMULATED LUMINESCENCE).

OSL dating is most routinely applied to silicate minerals, particularly quartz grains, and is based on the principle of measuring light-sensitive, trapped charge populations to determine the amount of time that has elapsed since natural minerals were last exposed to daylight. These charge populations accumulate at localized metastable defect sites within the crystal lattices of buried mineral grains as a result of exposure to ionizing radiation from the surrounding sediments (naturally occurring radioactive isotopes of potassium and rubidium, and isotopes in the uranium and thorium decay series) and

from cosmic rays. A small portion of the energy delivered by the ionizing radiation is stored in the form of trapped electrons, which continue to accumulate throughout the burial period at a rate proportional to the level of natural background radioactivity. Subsequent exposure of the mineral grains to light, as typically occurs during sedimentary erosion and transportation, causes previously accumulated charge populations to be evicted from the light-sensitive traps responsible for OSL production. As a result of this process, the OSL clock is reset to zero and the emitted OSL signal can be used to measure the amount of energy stored within the mineral during burial (Figure 1a).

The repeatability of the optical resetting and signal acquisition mechanism means that OSL dating is one of the few radiometric methods that can be used to directly constrain the timing of sediment deposition events. In archaeological studies, OSL dating offers a viable means of both reconstructing site formation histories and providing indirect ages on cultural artifacts or fossils buried within sedimentary deposits. OSL is particularly well-suited for dating a diverse array of archaeological settings because it can be applied to ubiquitously occurring natural minerals and it is applicable to both silt- and sand-sized sediment fractions (typically 4–11 μm to 212–250 μm). OSL techniques also have the advantage of yielding numerical ages that do not require subsequent calibration on the calendric timescale, and they are applicable over a broad age range that extends well beyond the ~50,000 year limit of radiocarbon dating.

An implicit assumption of OSL dating is that mineral grains have been exposed to sufficient daylight prior to their most recent deposition cycle to enable complete resetting of any pre-existing trapped charge populations (Figure 1a). If this is not the case, the mineral grains being dated may retain a sizeable residual OSL signal and the calculated age is likely to overestimate the true depositional age of the sediment (Figure 1b). The rapidity with which

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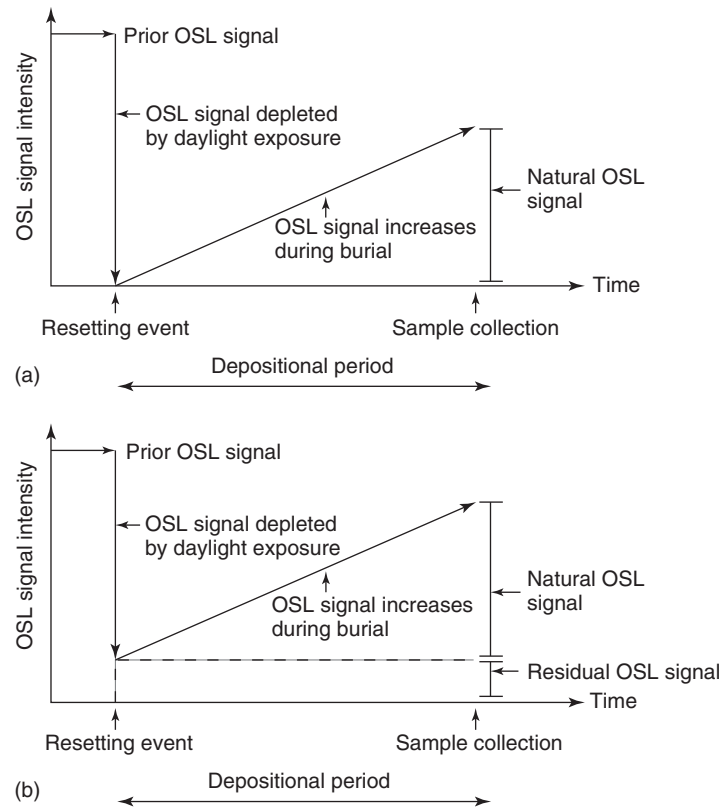


Figure 1 Schematic representation of the principles behind OSL dating. The graphs show how the relative size of the OSL signal changes with time following daylight exposure and burial at an archaeological site. Grains eroded from older sedimentary deposits initially have a large trapped charge population (prior OSL signal). Subsequent exposure of the grains to daylight during erosion or transportation reduces this trapped charge population (resetting event). Following burial and shielding from daylight, the trapped charge populations increase at a rate that is proportional to the level of environmental radiation until the grains are exposed to prolonged daylight and measured in the laboratory. (a) Ideal scenario in which all of the grains are exposed to prolonged daylight and the prior OSL signal is fully reset. (b) Scenario in which daylight exposure is more limited and the prior OSL signal is not completely reset. In this case, the post-burial OSL signal accumulates on top of a residual signal and the luminescence age overestimates the true depositional age of the sediment.

the main quartz OSL signal (the so-called fast component) bleaches in nature (on the order of a few seconds) means that adequate signal resetting is commonplace in aeolian environments characterized by prolonged subaerial daylight exposure. However, the potential for insufficient bleaching may need to be taken into consideration when dating certain types of archaeological sediments, particularly those accumulated by fluvial, colluvial or alluvial processes, or those deposited in caves or rock shelters.

A second important assumption of OSL dating is the absence of significant time-dependent changes in the surrounding sediment environment following burial. In particular, it is assumed that (1) the dated sediment has not been subject to major post-depositional mixing; (2) there have not been any significant time-dependent changes in sediment moisture content (or that any such temporal variations can be reasonably constrained); and (3) nuclides in the uranium and thorium decay series of the surrounding

sediment have remained immobile and/or in a state of secular equilibrium since deposition. Again, there may be instances in which these conditions are not upheld in complex archaeological settings, particularly in cave environments, and these complications must be adequately accounted for in the OSL age calculation.

OSL age calculation

To calculate an OSL age it is necessary to estimate the total radiation dose that has been deposited in a mineral grain since burial (the palaeodose) and the rate at which the accumulated radiation dose was delivered to the mineral grain in the natural environment (the dose rate). An empirical estimate of the palaeodose (known as the equivalent dose or D_e) is obtained by comparing the naturally accumulated OSL signal intensity with that obtained from a series of known doses administered using a calibrated laboratory radiation source (Figure 2a). The time elapsed since a sample was last exposed to daylight (sample burial age) may be obtained from the D_e and long-term dose rate estimate using the following equation:

$$\text{Age (ka)} = \frac{\text{Equivalent dose (Gy)}}{\text{Dose rate (Gy/ka)}} \quad (1)$$

where the amount of absorbed energy per mass of mineral is expressed in units of Grays (1 Gy = 1 J/kg).

OSL ages are given in calendric years before present (where “present” equates to the year of sample collection) and they are conventionally presented with their associated 1σ (68% likelihood) uncertainty ranges. The latter are primarily derived from random measurement and fitting uncertainties, systematic uncertainties on instrument calibration and conversion factors, and indirectly quantified uncertainties on burial history and dose rate parameters. For most archaeological samples, the combined 1σ OSL age uncertainties range between 5% and 10% depending on signal brightness, intra-sample D_e scatter, and time-dependent dose rate considerations (Aitken 1998).

The upper age limit for quartz OSL dating is dictated by the maximum number of trapped electrons that can accumulate at light-sensitive defect sites before they become completely filled or saturated, as well as the long-term stability of the trapped charge at ambient temperatures. At low dose exposures, the charge trapping rate, and hence OSL signal growth rate, is approximately linear owing to the large number of vacant electron trapping sites in the crystal lattice. Prolonged exposure to higher doses results in a tailing off of the OSL signal growth per unit radiation dose as the finite number of electron traps becomes progressively filled and it becomes increasingly unlikely for charge to be trapped at unoccupied defect sites. Eventually, when all of the available electron traps are filled, there is no additional OSL signal growth with continued radiation exposure and the upper dating limit is reached (Figure 2b). The rate of OSL signal growth with dose, characterized by the OSL dose–response curve, therefore conforms to a saturating exponential function of the form:

$$I(D) = I_{\max} \left(1 - e^{-\frac{D}{D_0}} \right) \quad (2)$$

where I is the OSL signal intensity associated with dose D , $I_{\max}$ is the maximum signal intensity at dose saturation, and D_0 describes the rate of OSL signal saturation with respect to dose and provides an indicator of the long-range dating potential of the OSL signal.

From a practical perspective, the upper limit for precise D_e determination is sometimes taken to equal roughly twice the D_0 value (~85% of the $I_{\max}$ value) on the grounds that D_e interpolation uncertainties become increasingly large as the dose–response curve approaches saturation (Figure 2b). Typical $2D_0$ values for quartz samples range between 100 Gy and 400 Gy, varying significantly on a sample-by-sample and grain-by-grain basis according to the number and type of available defect sites. Where the environmental dose rate is relatively low (e.g., 1 Gy/ka), such dose saturation limits permit reasonably precise dating back to 100–400 ka according to Equation 1. However, in higher dose rate environments (e.g., 2–3 Gy/ka), dose saturation will be reached over much shorter burial times and reasonably precise OSL dating may be restricted to within the last 100 ka. The

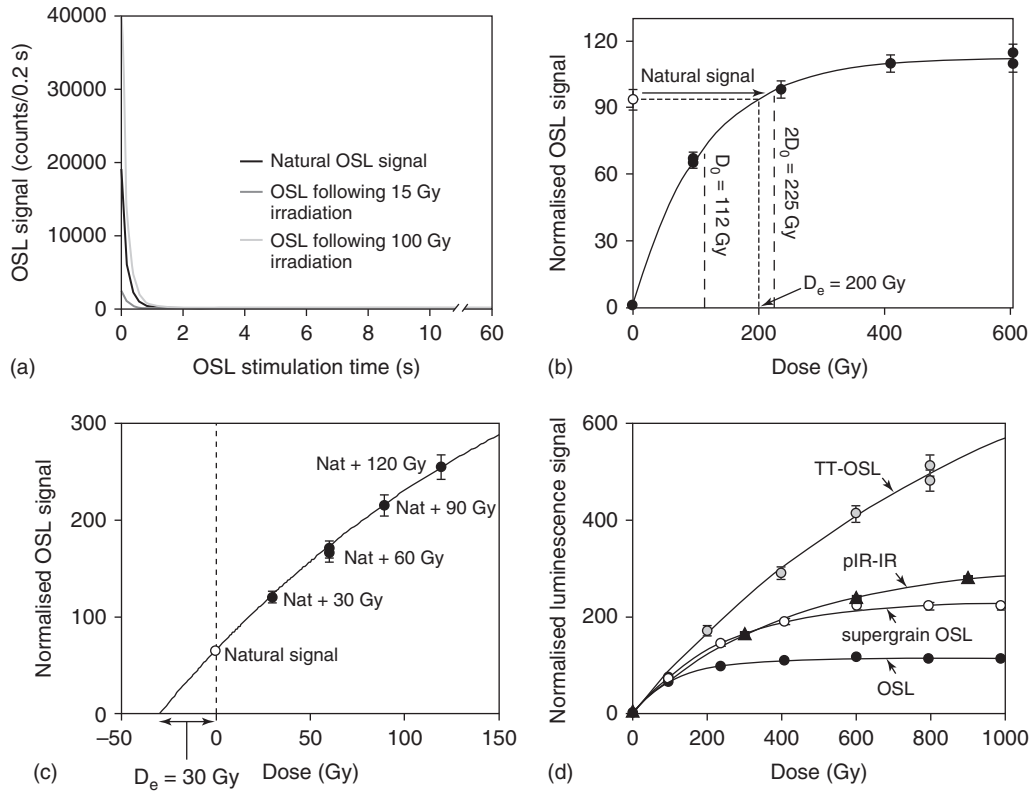


Figure 2 (a) Example quartz OSL decay curves for a multi-grain aliquot. The naturally accumulated OSL signal is compared with two OSL signals obtained after administering different-sized laboratory irradiations. (b) Regenerative dose response curve showing the relationship between OSL signal growth and laboratory dose. The equivalent dose (D_e) value is read off the x -axis and is determined by interpolation of the natural signal (white circle) onto the dose response curve. The characteristic saturation dose (D_0) value of the dose response curve is shown for comparison. (c) Additive dose response curve constructed by adding different laboratory doses to the natural signal (white circle). The dose response curve is extrapolated back to the x -axis intercept to calculate the D_e value. (d) Comparison of SAR dose response curves obtained using OSL, TT-OSL, pIR-IR, and supergrain OSL.

upper age range of quartz OSL therefore varies significantly depending on the D_0 and dose rate characteristics of a sample.

The lower dating limit for OSL is governed by the inherent luminescence sensitivity of the sample to low dose exposures and the minimum detection limits of the OSL instrumentation. In most instances, these restrictions impose practical lower OSL dating limits on the order of the last few centuries, decades, or even years under favorable bleaching conditions. However, OSL dating uncertainties are often relatively large (>50%) over subdecadal timescales.

OSL dating procedures

OSL samples need to be collected from archaeological sites without exposing them to daylight. This is usually accomplished by hammering opaque PVC or metal cylinders into cleaned sediment sections, excavating sediment blocks, or sampling material at night or during daytime underneath thick opaque sheeting with the aid of filtered lights. In the laboratory, silt-sized or sand-sized quartz/feldspar grains of interest are chemically and physically separated under strictly controlled lighting conditions, and sand-sized

fractions are additionally treated with concentrated HF acid to eliminate their alpha-irradiated outer layers (Aitken 1998).

Once the refined silicate fractions have been isolated, they are mounted on steel or aluminum discs using silicone oil (sand-sized grains), by hand-picking and brushing of individual grains (single-grain measurements), or by settling in acetone (silt-sized grains). The naturally accumulated OSL signals of these aliquots are then measured using specifically designed automated readers equipped with a filtered photomultiplier tube, an array of different LED and laser sources, a controlled heating device and an integrated irradiation source (e.g., Bøtter-Jensen, McKeever, and Wintle, 2003).

Two main approaches are used for determining the D_e value of OSL samples: additive dose and regeneration methods. Both approaches involve calibrating the naturally accumulated OSL signal intensity against a corresponding OSL dose–response curve constructed from different-sized administered doses. In the additive dose method, the dose–response curve is obtained by adding different radiation doses on top of the natural OSL signal for each aliquot or group of aliquots. The D_e value is then calculated by extrapolating the dose–response curve onto the x -axis intercept (Figure 2c). In the regeneration method, the dose–response curve is constructed after first removing the natural OSL signal and sequentially adding known doses to each aliquot or group of aliquots. The natural OSL signal is then interpolated onto the dose–response curve to determine the D_e value (Figure 2b). For both these methods, it is necessary to preheat the sample in order to isolate a thermally stable OSL signal, and to account for any OSL signal sensitivity change arising from repeated heating, OSL stimulation and irradiation (Aitken 1998).

To calculate the environmental dose rate of an OSL sample, it is necessary to determine: (1) the external gamma, beta and (if applicable) alpha dose rate arising from the decay of radionuclides in the surrounding sediment matrix; (2) the internal dose rate contribution from radionuclides found inside the dated mineral grains; and (3) the dose rate from cosmic rays that penetrate through the sediment overburden (Aitken 1985). Three main approaches are used to determine

the external dose rate component in archaeological contexts. The first involves measuring the concentrations of radioactive elements and their daughter products in subsamples of the surrounding sediment using techniques such as inductively coupled plasma mass spectrometry (ICP-MS), X-ray fluorescence, and instrumental neutron activation analysis. The second involves directly measuring radioactive emissions of indicator isotopes in the surrounding sedimentary matrix using techniques such as in situ NaI gamma spectrometry, thick-source alpha counting, low-level Geiger-Müller beta counting, and high-resolution gamma spectrometry. The latter is particularly advantageous in archaeological settings because it permits simultaneous measurement of different parent and daughter radioisotope emissions in the ^{238}U and ^{232}Th decay series, thereby enabling direct assessments of secular equilibrium in the burial environment. The third approach utilizes in situ assessments of luminescence dosimetry capsules that are highly sensitive to radiation exposure (e.g., aluminum oxide and calcium sulphate). Such dosimeters are left buried at the archaeological site for at least several months to provide a reliable measure of the present-day gamma dose rate at each OSL sample position.

The internal dose rate component can be similarly determined using emission counting techniques or assessments of elemental composition (e.g., using electron microprobe or laser ablation ICP-MS analyses of dated grain fractions). Cosmic ray contributions to the environmental dose rate are typically small (<10% of the total dose rate) and are usually estimated using empirically derived equations that take into account site altitude, geomagnetic latitude, and thickness of sediment overburden (Prescott and Hutton 1994). Account must also be taken of long-term sediment water content when deriving the environmental dose rate (Aitken 1985). Interstitial water exerts an attenuating effect on the external dose rate components, since it acts to absorb a fraction of the ionizing radiation that would otherwise reach the quartz or feldspar grains. Typically, the total dose rate for sand-sized quartz grains will vary by ~1% for a 1% change in sediment water content.

Methodological advances in OSL dating

The discovery that OSL could be used as a reliable quartz and feldspar dating tool was first made by Huntley, Godfrey-Smith, and Thewalt (1985), and was closely followed by the discovery that IRSL could also be used to date feldspar samples (Hütt, Jaek, and Tchonka 1988). These breakthroughs built on three decades of thermoluminescence research into establishing “firing event” chronologies for heated materials (ceramics, burnt stones, burnt sediment) and daylight exposure chronologies for unheated sediments. Unlike its progenitor, optical dating utilized only the most light-sensitive electron traps, and it was possible to completely reset the dating signal by relatively short daylight exposures. These advantages significantly reduced the chance of encountering samples with residual luminescence signals at burial, and enabled more reliable dating of archaeological sediments that had experienced shorter daylight exposures.

OSL dating of archaeological sites proliferated during the 1990s and 2000s courtesy of three methodological advances. The first turning point came with the advent of reliable single-aliquot D_e estimation procedures. Early OSL dating approaches required the measurement of large numbers of aliquots (~30–50) to produce a single D_e estimate for a sample. During the 1990s, such multiple-aliquot methods were largely replaced by single-aliquot methods in which all the measurements needed to determine a D_e value are undertaken on a single aliquot. Not only did this avoid problems of variable OSL signal sensitivities from aliquot to aliquot, but it also required less sample material for dating and permitted the generation of replicate D_e populations for each sample.

The emergence of the single-aliquot regenerative-dose (SAR) protocol heralded a second important methodological advance in OSL dating (Murray and Wintle 2000). The SAR protocol incorporated (1) improved D_e precision via interpolation rather than extrapolation of the dose–response curve, (2) a test-dose sensitivity correction procedure to circumvent problems of progressive OSL signal sensitization during repeated laboratory heating, irradiation and bleaching steps, and (3) the provision of several

in-built quality assurance checks on OSL properties, which afforded added robustness to the resultant ages.

The third key advance in OSL dating was the introduction of single-grain OSL techniques, which involved measuring D_e values for individual sand-sized grains rather than individual aliquots containing tens, hundreds, or even thousands of grains. Technological developments in automated single-grain readers during the late 1990s made it practical to measure very large numbers of individual grains in a reasonable amount of time and, thus, to generate statistically significant replicate D_e datasets for each sample. By examining the structure of these single-grain D_e distributions, it is now possible to gain detailed insights into sedimentary complications that might otherwise give rise to multi-grain aliquot OSL age inaccuracies, and to isolate subpopulations of grains that exhibit the most suitable luminescence properties for dating. Single-grain approaches have proved to be particularly advantageous in archaeological contexts, which are apt to suffer from a wide range of bleaching conditions and post-depositional mixing processes (Jacobs and Roberts 2007). The advancement of single-grain OSL dating in archaeological contexts has been further aided by the development of improved statistical techniques for obtaining more representative burial dose estimates from complex D_e datasets (Galbraith and Roberts 2012).

Recent and future developments

Recent developments in OSL archaeological research have focused on extended-range dating signals that display much higher dose saturation limits than the conventional OSL signal. Such extended-range techniques include TT-OSL dating of quartz, single-grain OSL dating of quartz supergrains with very high D_0 values, violet stimulated luminescence dating of quartz, and pIR-IR dating of K-feldspar grains. These approaches offer the potential to extend the traditional upper age limit of quartz OSL by a factor of 2–5, or more (Figure 2d), and to establish archaeological chronologies spanning larger parts of the Middle Pleistocene hominin record. Research is

ongoing to assess the long-term stability of these extended-range signals, and to evaluate their broader reliability across different archaeological contexts using independently dated samples. Existing known-age comparisons of TT-OSL, pIR-IR and supergrain chronologies show good potential for reliable dating over Late and Middle Pleistocene timescales (Arnold et al. 2015). However, these novel approaches are likely to offer the greatest benefit when applied in tandem, and when applied at the single-grain scale of analysis.

Significant advances have also been made using three-dimensional simulations of dose rate environments with Monte Carlo platforms such as Geant4. These modelling frameworks are likely to herald improved reliability in dose rate calculations at archaeological sites exhibiting spatially complex radiation fields, and a better understanding of single-grain D_e scatter arising from beta dose rate heterogeneity.

The next generation of OSL dating research is likely to lie in spatially resolved D_e and dose rate measurements made using photon counting imaging systems and autoradiography interfaces. Several custom-built and commercially available EM-CCD systems have been developed for spatially resolved OSL dating purposes over the last few years. Efforts are now focused on improving hardware and data processing capabilities, and establishing reliable and precise methodologies for in situ OSL dating of intact sediment slices.

SEE ALSO: Dating and Electron Spin Resonance (ESR); Dating and Infrared Stimulated Luminescence; Dating Ceramics and Luminescence

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Dating Ceramics and Luminescence

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Luminescence dating of ceramics was first introduced in the late 1970s (Aitken 1985). Only in the last 20 years has its use become widespread, partly because of methodological developments that have increased its precision. As a direct method of dating heating events, it has been able to address some chronological problems in ceramic studies that were not feasible before.

Introduction

Use of ceramic style to construct archaeological chronologies has a long and mostly successful history, but such use is restricted to ordinal scales and is not always easy to apply to individual ceramics. The promise of ratio scale (absolute) dates for ceramics was first realized in the 1970s and 1980s by the development of luminescence dating. More recently, radiocarbon dating has been applied to ceramic residues and to temper. While this has great potential in selected applications, it is plagued by association problems linking the age of ceramic manufacture with the radiocarbon age. Another new development is dating ceramics using rehydration rates, but this method still requires additional research. Luminescence has the advantage of a close match between the manufacturing age and the event dated by luminescence, which is the last exposure to sufficient heat (or light). It works on ubiquitous materials, quartz and feldspar, which are found in most ceramics, making it one of the most widely applicable dating methods in archaeology.

While it has often been used as a second choice to radiocarbon dating, where radiocarbon-datable materials are either unavailable or unreliable, such usage, for example, in trying to date features which contain ceramics,

may have the same association problems as radiocarbon, depending on the target event. Rather, the most singular value of luminescence is its ability to date manufacturing events directly. It can thus be used to measure technological change, isolate different components of mixed assemblages, and assess occupation duration. Beyond pottery, it can be applied to many structural materials such as bricks, adobe, daub, and burned clay (see a recent review by Bailiff 2014).

Technical aspects

Luminescence is based on the ability of some minerals to store absorbed energy from natural radiation for lengths of time much longer than the history of ceramics. This energy, stored as ionized particles trapped in crystalline defects, is released upon heating or exposure to sunlight, producing a luminescence signal. The intensity of this signal is proportional to the time since last heating or light exposure. The accumulated dose (or paleodose) can be measured as luminescence either by heating the sample (thermoluminescence, or TL) or by exposing the sample to a narrow wavelength of light (optically stimulated luminescence, or OSL). Calibrating the sensitivity of the signal against laboratory irradiation (resulting in an equivalent dose, D_e), and dividing by the dose rate (the amount of irradiation received by the sample per unit time) yields an age. With some exceptions, the dose rate does not change significantly through time. Historically, ceramics were dated by TL, but in recent years, most dating has been done by OSL, although TL is still used.

The dose rate comprises alpha, beta, and gamma radiation, with some contribution from cosmic radiation. These kinds of radiation have different effective ranges. Alphas range up to 20 μm , betas up to 3 mm and gammas up to 30 cm in ceramics or sediment. The cosmic range is even greater yet, but is usually barely significant. When sampling the ceramic, if the outer 2 mm are removed or avoided, then the luminescence

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of the ceramic will be a function of alphas and betas from only the ceramic itself, gammas from the ceramic and the surrounding sediment, and cosmic radiation. Thus to determine the total dose rate, it is necessary to measure not only the radioactivity of the ceramic, but also of its immediate surroundings. Gamma dose rates can be measured in the field, but this is rarely done for ceramics because these surroundings are often destroyed during excavation. Rather, a sample of the surroundings is collected and sent to the laboratory for measurement. The more complicated the surroundings (which might include rocks, other artifacts, architectural remains, and organics as well as sediment), the more difficult it is to determine a precise gamma dose rate. Fortunately, in many, but by no means all, situations, radioactivity across a site does not vary much. Sometimes archaeologists want to date ceramics but have no sediment sample, for example, with museum specimens. This can be done if reasonable approximations of the external dose rate can be made, although at a cost of precision.

In terms of which minerals in a ceramic to date, there are two options. The first option is to date coarse-grain (90–250 μm) inclusions. Most often, quartz inclusions are isolated. While feldspars may also be used, heating tends to increase the sensitivity of quartz while reducing the sensitivity of feldspars. Feldspars also suffer from an athermal loss of signal through time called anomalous fading. Fading can be corrected for, but only at a cost of precision. Quartz is therefore usually preferred unless it is absent or of particularly low sensitivity. The other option is to date polymineral fine grains (1–8 μm). This has some advantages. First, ceramics often do not contain sufficient numbers of coarse grains, and, second, fine-grain dating is less dependent on external dose rate. In coarse-grain dating, the inclusions lack a source of short-range alpha irradiation. While this avoids special problems with alpha irradiation, it means the dose rate is dominated by beta and gamma radiation. Betas arise from the ceramic itself (if the outer 2 mm is removed), but gammas, which can make up as much as half the dose rate, come from the immediate surroundings. If ceramics come from complex environments, estimating the gamma dose rate can be difficult and error-prone. With fine-grain analysis, however, the alpha

contribution has to be considered along with the betas and gammas, the gammas now only contributing about a quarter of the total dose rate, allowing more tolerance in their uncertainty. The disadvantage of fine-grain analysis is the difficulty in removing feldspars from the sample, and anomalous fading must be taken into account.

To determine D_e by TL, multi-aliquot methods are normally employed. The two most common are called additive dose (where different laboratory doses are added to the natural doses of several aliquots to form a growth curve plotting dose against TL, and D_e is determined by extrapolation) and regeneration (where laboratory doses are applied to aliquots which have been zeroed by heat and the natural signal is interpolated into a subsequent growth curve to determine D_e). Both methods have problems with sensitivity changes, which can be minimized by combining both methods in what is called the slide method. For fine-grain samples, the TL signal has to be corrected for fading. D_e from OSL is usually determined for coarse grains by the single-aliquot regeneration (SAR) method (Wintle and Murray 2006), which uses test doses of equal magnitude to correct for sensitivity changes brought about by successive irradiation, preheating and stimulation. Because D_e is determined on just one aliquot, precision is improved (obviating any need to normalize among aliquots) and it also becomes possible to measure multiple aliquots to document any variation in D_e that might be present, due to uneven heating or heterogeneity in the distribution of radiation sources (mainly from betas), among other causes. Scanning equipment to measure D_e from individual grains within a ceramic slice has been used to detect spatial variation in D_e to the same effect. Future research promises to couple some kind of scanning equipment for luminescence with a method for detecting differential dose rate (e.g., placing a sheet of $\text{Al}_2\text{O}_3:\text{C}$, a powerful dosimeter, across the slice). Different ages for different parts of the ceramic could then be obtained.

For fine-grained samples, a “double” SAR has been developed, where infrared stimulation (IRSL) precedes each OSL stimulation (usually with blue light). Feldspars, unlike quartz, are sensitive to IRSL, and are also the main sources of anomalous fading. The rationale is that the

preceding IRSL will reduce the feldspar signal, so that the subsequent OSL will be dominated by the contribution from quartz, and thus not fade. This is particularly the case where original heating of the ceramics has reduced the feldspar sensitivity while increasing that of quartz. Nevertheless, feldspars are also sensitive to OSL, and in some samples, the IRSL will not remove the feldspar signal, so that feldspar contributes to the subsequent OSL, which may then be subject to fading. The OSL may then only provide a minimum age unless fading is corrected (a time-consuming process). Another way to gauge whether the OSL signal is mainly coming from quartz is to measure the *b*-value. This is a measure of alpha efficiency (another method is called *a*-value). Because of their short range, alphas do not travel far enough for all of their energy to get absorbed as trapped charge. Thus they are less efficient at producing luminescence than betas or gammas. The *b*-value compares the sensitivity of the sample to alpha and beta irradiation (the latter about 10 times more effective), and uses this ratio to correct the alpha dose rate. The *b*-value for quartz ranges between about 0.4 to 0.7, while the *b*-value for feldspar is much higher. Measuring the *b*-value for OSL provides one indication of whether the OSL signal is dominated by quartz or not, and thus the likelihood of fading. Often both TL and OSL are measured. This is because OSL sometimes produces unreasonably old ages. While the cause is uncertain, it may be because the OSL fast bleaching component was either originally absent or destroyed during original heating, so that only a slow bleaching component remains, and this may not have been reset by the original heating. Obviously, where agreement in age between OSL and TL is obtained, the highest confidence can be placed in the age.

Some ceramic sherds pose difficulties in dating, usually because of the absence of suitably sensitive minerals. Ceramics from volcanic regions, for example, are often problematic, the Pacific Islands being a prime example. The feasibility of measuring volcanic quartz with TL using red emission (as opposed to the usual blue emission), however, has been demonstrated on Japanese pottery.

Aside from these exceptions, however, many sherds are datable, and to a precision often better than 10%. In terms of accuracy, a simulation study

showed that with quartz dating of pottery, D_e values obtained on given burial doses could achieve an accuracy of better than 10%. Fewer empirical comparisons have been done systematically, although many studies show ceramic dates to agree with independent evidence in most cases. A comparison of results between two laboratories on 25 sherds from North Carolina showed some divergences, mostly because of different procedures followed, but the results from either lab agreed broadly with independent chronological evidence. The study shows that dates are not just numbers from a black box, but estimations that need evaluation both from the luminescence and the archaeological perspective.

Applications

Many requests for dating ceramics that come into the University of Washington laboratory, a major provider of ceramic dating, reflect luminescence as a second choice because material for radiocarbon dating was not available, had association problems for the event of interest, or provided low precision because of flatness in the calibration curve. Yet there are chronological problems where luminescence should be the first choice, rather than something turned to because other dating is not viable. Such applications are the focus in this section.

For time periods when ceramics form a large portion of the archaeological record, the smallest unit of analysis, in some sense, is the ceramic sherd. Knowing the manufacturing date of each sherd could provide a wealth of information of archaeological interest, but of course would be prohibitively expensive. Projects dating 30–40 ceramic sherds have been performed, but even smaller numbers could potentially yield useful information given prudent sampling. For example, in testing whether different sites in the Lower Mississippi valley overlapped in their durations, one study sampled from just one stylistic type to see if the presence of that type among the sites was chronological or just represented spatial interaction. A sample of 10, while still small, was able to answer the question. In a similar vein, another study used luminescence to date particular stylistic types to show that pueblos in New

Mexico may have been abandoned much later than was suggested by tree-ring dating (which dates a different event). Using luminescence to address occupation issues, however, assumes that the time between manufacture (the event luminescence addresses) and discard is relatively short, which is often the case with cooking ware. There are cases where this time could be long, as in the case of heirlooms. Ceramic inhaling bowls on the Caribbean island of Carriacao were found by luminescence to be several hundred years older than the earliest radiocarbon dates on the island.

All archaeological sites are to some degree palimpsests: time-averaged mixtures of artifacts deposited at different times. A key object of archaeological research is to separate these palimpsests into temporally distinct components to the extent possible. Luminescence provides one solution to this problem for ceramic-bearing sites. One study showed that large enclosure pits in the UK contained ceramics dating to a wide range. The larger the pit, the more likely this was the case. Another study found that ceramics from pits in an Illinois site date to a much wider range than radiocarbon dates (based on combined charcoal pieces) suggested, resolving some typological issues of whether certain types had longer temporal ranges or not. At a regional scale, luminescence can help determine whether different sites are the same age or not. For example, in Arkansas, luminescence showed that small “farmsteads” pre-dated the occupation of large centers.

Sherds may not be the only datable material. Monumental architecture is often composed of bricks (fired, or unfired as in the case of adobe). Dating individual bricks can be a way of determining different stages of construction, evidence of repair, and repeated use of old bricks (Bailiff 2007). Other ceramic material, such as mortar, can be dated. While somewhat off the topic of this article, luminescence has long been applied to burned lithics, including fire-cracked rocks, so these too can serve as basic dating units.

Tracing technological change is challenging in archaeology, partly because of the reliance on similarity-based dating techniques, such as seriation and ceramic cross-dating, or on stratigraphy, both anchored by radiocarbon or some other dating method. The target event for these methods is usually the occupation, to which an assemblage of artifacts is assigned. Such dating

sets up boundaries between assemblages (often referred to as phases) and puts emphasis on discontinuities rather than the continuous nature of change. This makes change seem transformational. First one kind of ceramic was made, then another. Change is more likely selectional, where the frequencies of different kinds of ceramics change through time. One ceramic type increases at the expense of another. This kind of change might be measurable if the target is the date of manufacture rather than the occupation. This was demonstrated by Feathers (2009), who was looking at the rise of shell-tempered pottery in the southeastern US. In northern Alabama, the conventional wisdom is that shell-tempered pottery rather abruptly replaced grog-tempered pottery, with some overlap at “transitional” sites. Luminescence dating of individual sherds, however, showed that some shell-tempered pottery appeared quite early and some grog-tempered pottery appeared quite late, so the change was a change in frequency, not an abrupt introduction of shell-tempered pottery.

SEE ALSO: Dating and Infrared Stimulated Luminescence; Dating and Optically Stimulated Luminescence; Dating (Burnt) Lithics; Dating in Archaeology; Optically Stimulated Luminescence; Seriation; Thermoluminescence

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Dating Pollen

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Introduction

Pollen grains, the male microgametophytes of seed plants (angiosperms and gymnosperms), are widely distributed in the environment and accumulate in a range of sedimentary environments including lakes, bogs, caves, floodplains, and the deep oceans. While some components of pollen grains such as the generative nucleus degrade quickly in the environment, the resilient pollen wall can be preserved for thousands to millions of years. The widespread distribution and high preservation potential of pollen grains underline the value of ancient or “subfossil” pollen not only as a tool for reconstructing past vegetation history and environmental change (see *PALYNOLOGY*), but also as a sample material for radiocarbon dating. The wide variety of deposits that have been successfully dated from pollen include peats, lake sediments, aeolian deposits, packrat middens, and Pleistocene ice-wedge casts. Key advantages of pollen as a dating material are that it may be present in deposits where plant macrofossils are scarce or lacking, and it can be identified in terms of the source vegetation, unlike bulk material where the provenance is unknown.

Basis of the approach

Pollen grains, along with the spores of terrestrial lower plants (ferns and mosses), possess several characteristics that make them highly suitable for radiocarbon dating. The pollen wall is composed of the organic biopolymer sporopollenin, which is rich in carbon in the form of both long-chain macromolecules and aromatic compounds. Carbon in sporopollenin is derived from atmospheric CO₂ through photosynthesis, incorporating photosynthates that are either

newly acquired during the pollen development stage or derived from stored reserves of at most a few years' age (e.g., Davis and Sparks 1971). Pollen grains therefore provide a reliable and effectively instantaneous “snapshot” of carbon isotopic ratios in the atmosphere during the time of pollen development. Fractionation effects (differential uptake of heavy and light carbon isotopes) occur during photosynthesis, but these are assessed by the parallel measurement of radioactive (¹⁴C) and stable (¹³C) carbon isotopes and are corrected for in the reporting of radiocarbon dating results. Sporopollenin is furthermore remarkably resistant to chemical attack, meaning that pollen grains are inert in the environment and can be considered closed systems with respect to the pool of carbon within them. Finally, the morphological characteristics of pollen grains mean that they can be identified to different taxonomic groups (typically families, genera or species), providing valuable contextual information for the dated sample.

Preparation procedures and practical considerations

Dating of pollen requires the preparation, in a suitably equipped laboratory, of a pollen-rich organic residue or pollen concentrate. This process shares many stages with the preparation of pollen residues for microscopic analysis, while avoiding carbon-containing chemicals (e.g., acetic anhydride, used in acetolysis, and ethanol). Typically, a combination of digestion stages in acidic and alkaline reagents is used to remove carbonates and humic acids from the peat or sediment sample, followed by deionized water washes to remove clay particles. Finally, the concentration of pollen grains is achieved through separation of the organic fraction using dense media (heavy liquids) and microsieving. Dense media separation may either be undertaken at a single target density (e.g., 1.5 times the density of water, or 1.5 SG) in which pollen grains, which have a typical density of slightly less than 1.5 SG

(Régnell and Everitt 1992), float, or at a series of decreasing densities (e.g., from 1.6–1.15 SG), allowing selection of the purest residue(s) for dating (Vandergoes and Prior 2003). Alternatives to density separations include manual selection of individual grains using a micromanipulator (e.g., Long, Davis, and De Lanois 1992), and isolation of pollen grains using flow cytometry (Tennant et al. 2013). However, the former technique is generally too time-consuming to be practical unless very large pollen grains such as *Picea* are abundant, and the latter has yet to be routinely applied for radiocarbon dating. Sieving using nylon mesh can be used to further concentrate organic particles within the size range of pollen (typically ~20–80 µm, but this may be tailored to suit the predominant pollen types in a specific sample) (Brown et al. 1992).

At each stage of the preparation, it is helpful to inspect the content of the residue under a high-powered transmitted light microscope, using a fine Pasteur pipette to extract a minute droplet of residue and placing it on a microscope slide under a coverslip. This allows the efficacy of the preparation stages to be assessed and modifications to be implemented as necessary, for example in selecting suitable sieve mesh apertures with respect to the size classes of both target pollen types to be retained and any undesirable organic components to be removed. Visual inspection and quantitative estimation (e.g., tally count of objects) of the purity of the pollen concentrate is essential, since the efficacy of the pollen concentration preparation may be strongly influenced by site- and sample-specific characteristics including total pollen concentration in the deposit, as well as the composition and proportions of different organic matter types (pollen, terrestrial plant spores, algal spores, fungal spores, microcharcoal, wood fragments, leaf tissues, etc.).

Particular attention must be paid to maintaining a clean working environment and avoiding contamination with modern carbon in the form of ambient dust, pollen, powders, oils, and so on. This does not require the use of a certified clean-room facility, but simply special attention to minimizing exposure to contaminants by common-sense means, including wearing powder-free gloves at all stages, working with capped centrifuge tubes, pre-cleaning glassware

and foil by heating to 500°C in a furnace, and thoroughly rinsing plastics (tubes, mesh, etc.) in deionized water. In light of the small sample size of pollen concentrates and the fairly intense pre-treatments required, it is advisable to undertake the parallel processing and dating of one or more laboratory standards to rule out contamination with modern carbon and to allow for correction factors to be applied if necessary. In any case, it is advisable to discuss the strategy for pollen concentrate dating with the radiocarbon facility prior to undertaking the preparation procedure.

Pollen concentrates should be dried or freeze-dried prior to measurement of the dry weight of sample submitted for dating. Advances in the measurement of small samples and widespread availability of the AMS technique mean that samples containing as little as 200 µg of carbon may be dated at many globally distributed radiocarbon facilities, and even smaller samples may be dated at some facilities. When assessing the size of samples for analysis, it should be taken into account that the pollen concentrates may not be composed entirely of pollen, and that pollen itself is only composed of around 50% carbon. In practice, dry sample weights of around 5–15 mg are recommended. While these amounts are small, quite large quantities of starting material may be required to produce pollen concentrates of sufficient size. At the outset, it is helpful to know the absolute concentration of pollen in the sediment sample, as commonly estimated through the addition of an exotic marker such as *Lycopodium* spores. This approach, of course, cannot be used *directly* in the exact sample to be dated. In a recent case study, approximately 15 g of dry lake sediments with a typical pollen concentration of ca. 200,000 grains per cm³ were used to generate pollen concentrates ranging from 1–9 mg dry weight and 48% carbon content (Fletcher et al. 2017). Higher, or lower, pollen concentrations in the material would allow for smaller, or demand larger, starting samples, respectively.

Interpretation of pollen dates

In common with all dating approaches, attention should be paid to the characteristics of the sample material when interpreting the results of the radiocarbon dating. In principle, a sample of pollen grains should not be subject to uncertainty associated with dating samples from long-lived organisms, such as wood or charcoal, in which carbon accumulates sequentially over considerably longer timescales (decades to centuries). In practice, however, a sample of ancient pollen extracted from a sedimentary deposit will typically integrate pollen released over multiple seasons of pollen production, depending on the sedimentation rate of the deposit. Nevertheless, the resulting age of the pollen concentrate should provide an accurate estimate of the time of incorporation of pollen into the deposit. In the context of a continuously accumulating deposit, the age of the pollen concentrate will therefore indicate the time of deposition and provide a suitable basis for the development of depositional models and estimation of sedimentation rates. Two potential sources of uncertainty should be considered, namely reworking of old pollen from soils or sediments (e.g., Howarth et al. 2013), and incorporation of organic matter derived from aquatic production in deep lakes and hardwater settings (e.g., Fletcher et al. 2017). Both problems may result in ages that are older than the time of deposition, due either to the incorporation of non-contemporaneous (old) pollen grains, or contemporaneous organic matter containing old carbon associated with aquatic reservoir effects (MacDonald, Beukens, and Kieser 1991). The best guard against misinterpretation is good knowledge of the composition of the dated sample derived from visual inspection of the pollen concentrate prior to dating, accompanied by good contextual (geological, geomorphological, hydrological) information about the site. Comparison of the pollen concentrate ages and other dating results, such as radiocarbon dates on terrestrial plant macrofossils where available, can be highly

informative regarding the detection of reworking or reservoir effects.

SEE ALSO: Radiocarbon Calibration and Age Estimation

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Dating Rock and Desert Varnish

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Introduction

Desert varnish, or rock varnish in general, is a slow-accreting (1–40 $\mu\text{m}/\text{ky}$) manganese–ferrous dark coating on subaerially exposed rock surfaces (Perry and Adams 1978; Dorn and Oberlander 1981; Liu and Broecker 2000). It often reaches a typical thickness of 50–200 μm when fully developed (Figure 1a). Although formed in nearly all kinds of climatic settings, varnish is mostly seen in arid to semiarid deserts of the world. It comprises up to two-thirds of clay minerals, a quarter of manganese (Mn) and iron (Fe) oxides, plus several dozen minor and trace elements. Mn is typically enhanced over Fe more than by a factor of 50 above potential source materials such as dust, soils, water, and the underlying rock (Figure 1c). Three hypothetical models have been proposed to reconcile the enrichment of Mn in varnish formation (Dorn 2009). The biotic model posits that microbial agents colonizing rock surfaces preferentially fix Mn in accreted clays from desert dust. The abiotic model states that Mn enrichment is a physicochemical process involving mobilization from desert dust by pH-Eh fluctuations and precipitation events. The hybrid model claims that varnish formation is attributed to a combination of processes, where slow-growing bacteria fix Mn and Fe, which are then abiotically cemented by clay minerals. Despite decades of extensive research on the subject, the real mechanism of varnish formation is still poorly understood. One thing is, however, clear: its source materials come largely from airborne dust and dew rather than from the weathered substrate rock. This fact points to microscale sedimentary processes involved in the varnish deposition on rock surfaces.

Because of its sedimentary origin, varnish contains a laminated microstratigraphy that records past environmental fluctuations, especially wetness variations (Figure 1b). In the Great Basin of the western United States, Mn- and Ba-poor varnish layers, which are orange-yellow in ultrathin sections (5–10 μm thick) under transmitted polarized light, were formed during the overall dry period of the Holocene; Mn- and Ba-rich dark layers were deposited during the last glacial period when the Great Basin was much wetter than it is at present (Broecker and Liu 2001; see Figure 1b–c). Wet events represented by the glacial-age dark layers in the western US varnish correlate in time with cold episodes of the Younger Dryas (YD) and Heinrich events (H1–H6) in the North Atlantic region (Liu et al. 2000; Liu and Broecker 2007). Fine-grained and fast-accumulating varnish also records late Pleistocene and Holocene millennial-scale wet events synchronous with millennial-scale cooling events in the North Atlantic and Greenland (Bond et al. 1997, 1999; see Figure 2). These findings give rise to the use of varnish laminations (VML) as a dendrochronology-like age-dating tool.

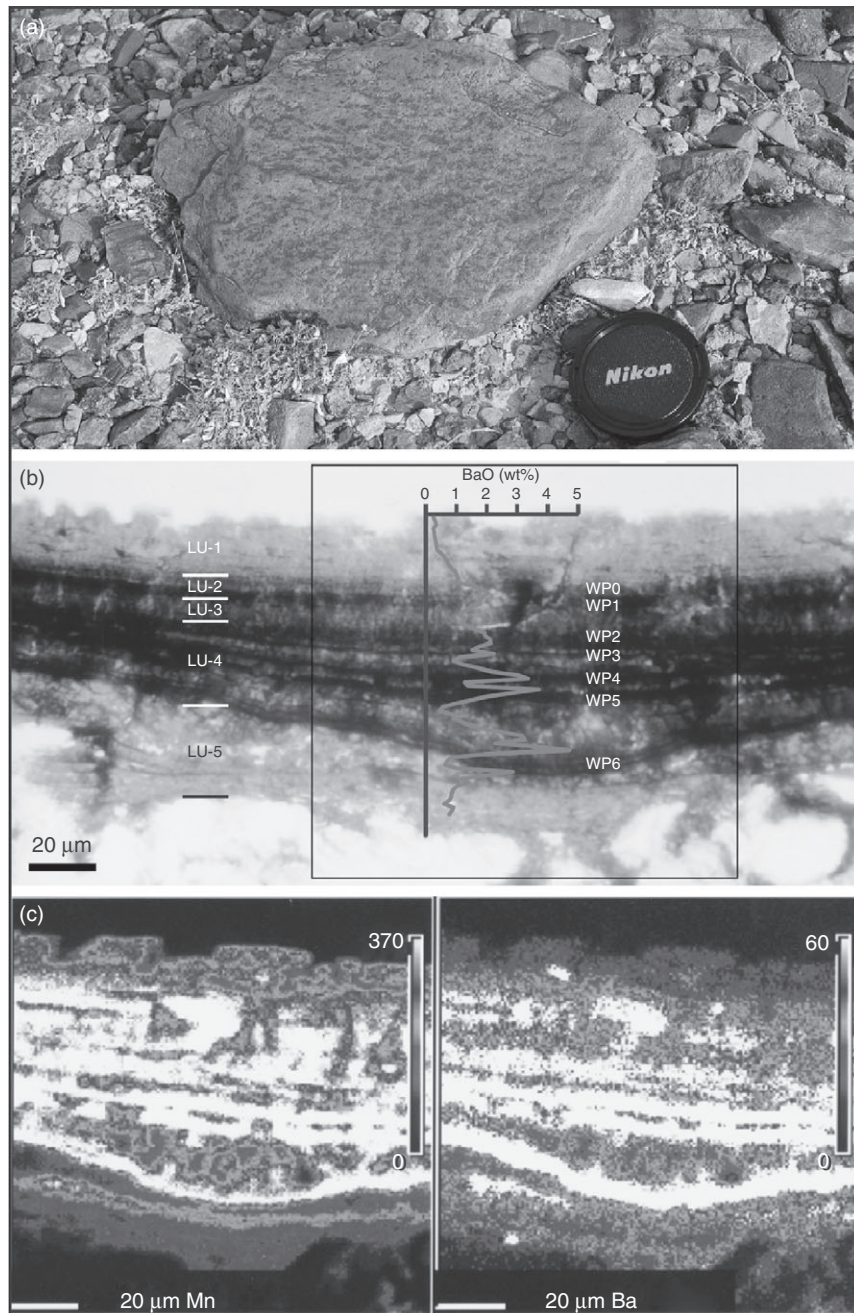
Principle and method

The basic premise of VML dating rests on an empirical observation that the formation of varnish microstratigraphy is generally tied to regional and global climatic variations: Mn- and Ba-rich dark layers formed in relatively humid periods, while Mn- and Ba-poor orange-yellow layers formed in relatively dry periods. Because climatic signals recorded in varnish are regionally and globally contemporaneous, once radiometrically calibrated and climatically correlated, VML can be used as a correlative dating tool to yield minimum-limiting surface exposure ages for varnished geomorphic and geoarchaeological features in the world's deserts. A rigorous blind test of this method was conducted on late Pleistocene lava flows in the Mojave Desert, California (Liu 2003; Phillips 2003). The convergence between cosmogenic ^{36}Cl ages and VML age estimates for

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three basalt flows in the Pisgah, Cima, and Amboy volcanic fields demonstrates that VML is a valid geochronological tool (Marston 2003). Recent studies (Liu and Broecker 2007, 2008, 2013) extended the VML dating potential to ~ 300 ka.

VML dating starts with varnish sample collection in the field. Because varnish accretes in a time-transgressive fashion within millimeter-sized microbasins on subaerially exposed stable rocks, the oldest possible varnish on a given

Figure 1 (a) Desert varnish formed on a ~70 ka desert pavement surface in Death Valley, California. (b) Visual microstratigraphy seen in varnish ultrathin section under a microscope with transmitted polarized light. (c) High-resolution ($128 \times 128 \mu\text{m}$) electron microprobe elemental mapping of manganese (Mn) and barium (Ba) abundance in desert varnish from Death Valley. The mapped area is framed in image (b) and the color scale of elemental concentration is shown on the right side of each panel. The zigzag curve depicts the probe line profiling for Ba. LU-1 to LU-5 represent five layering units (LU) recognized in the generalized master layering sequence for the western US drylands, and WP0–WP6 denote seven Mn- and Ba-rich major dark layers, interpreted to represent seven major wet periods during the last glacial time. These periods correlate in time with the cold episodes of the Younger Dryas (YD) and Heinrich events H1–H6. The Mn- and Ba-poor surface top layer (LU-1) and basal layer (LU-5) represent periods of dry climate during the Holocene and the last interglacial, respectively. Reproduced with permission from Liu and Broecker 2013. © Elsevier.

rock surface should be collected to maximize the chance of getting VML age estimate close to the surface exposure of the dated rock. This way of sampling is, however, experience-dependent and needs years of training and practice in the field. To sample surface geoarchaeological features such as stone artifacts and petroglyphs, a battery-driven mini-dremel attached to a diamond-coated drill bit is often used to acquire a 3-mm-long and 4-mm-sized mini-core that hosts the oldest varnish-filled microbasin. The sampled spot may be visually restored by inserting a varnish-coated mini-core of similar size from nearby rock of the same lithology.

In the lab, ultrathin sections of varnish-retained mini-cores are made using an innovative thin-sectioning technique, which permits examination of varnish microstratigraphy (Liu and Dorn 1996). The conventional way of making varnish thin sections cannot be employed, because the resulting sections are too thick (25–30 μm) and do not reveal visual microstratigraphy, which is opaque in normal geological thin sections. Varnish ultrathin sections are then photographed using a Leica DMLB light microscope equipped with a Leica MPS 60 Photoautomat system. Polarized light is used to increase image contrast. The use of a 10 $\times$ eyepiece in combination with a 40 $\times$ objective lens yields images with 400 $\times$ magnification of varnish microstratigraphy for layering pattern analysis. Electron microprobe is also used to acquire high-resolution (~2 μm) elemental mapping and line profiling of varnish microstratigraphy. These chemical data allow quantitative characterization of Mn, Ba, and other elemental fluctuations in varnish

microstratigraphy and assist in layering pattern interpretation.

Radiometric age calibration of a generalized master layering sequence constitutes the most difficult task in VML dating. Because of the limitations of available radiometric means such as radiocarbon and cosmogenic radionuclide methods, direct dating of individual layers in varnish microstratigraphy is not yet possible. The only feasible approach at present is collecting varnish from a geomorphic surface of known age and using this age as a maximum-limiting time constraint for initial deposition of the basal layer in varnish microstratigraphy (Liu and Broecker 2007). In addition, there is an unknown lag time between the surface exposure of a rock face and the subsequent varnish initiation on it, which often introduces uncertainties in the radiometric age calibration of the varnish layering sequence. New studies (Liu and Broecker 2018) indicate that, under favorable conditions, about 100 years or fewer may be needed for the very first varnish to initiate on subaerially exposed stable rock surfaces in arid to semiarid deserts. This finding suggests that, by deliberately sampling the oldest possible varnish on a well-dated surface, it is possible to reduce the lag time-related uncertainties in age calibration of the varnish layering sequence to about 100 years.

Climatic correlation of the wetness variations recorded in varnish microstratigraphy is critical for VML dating, which determines its intrinsic age resolution and regional applicability. Paleoclimate studies (Bond et al. 1997, 1999) indicate that the late glacial and Holocene climate history of the Earth is characterized by rapid, millennial-scale

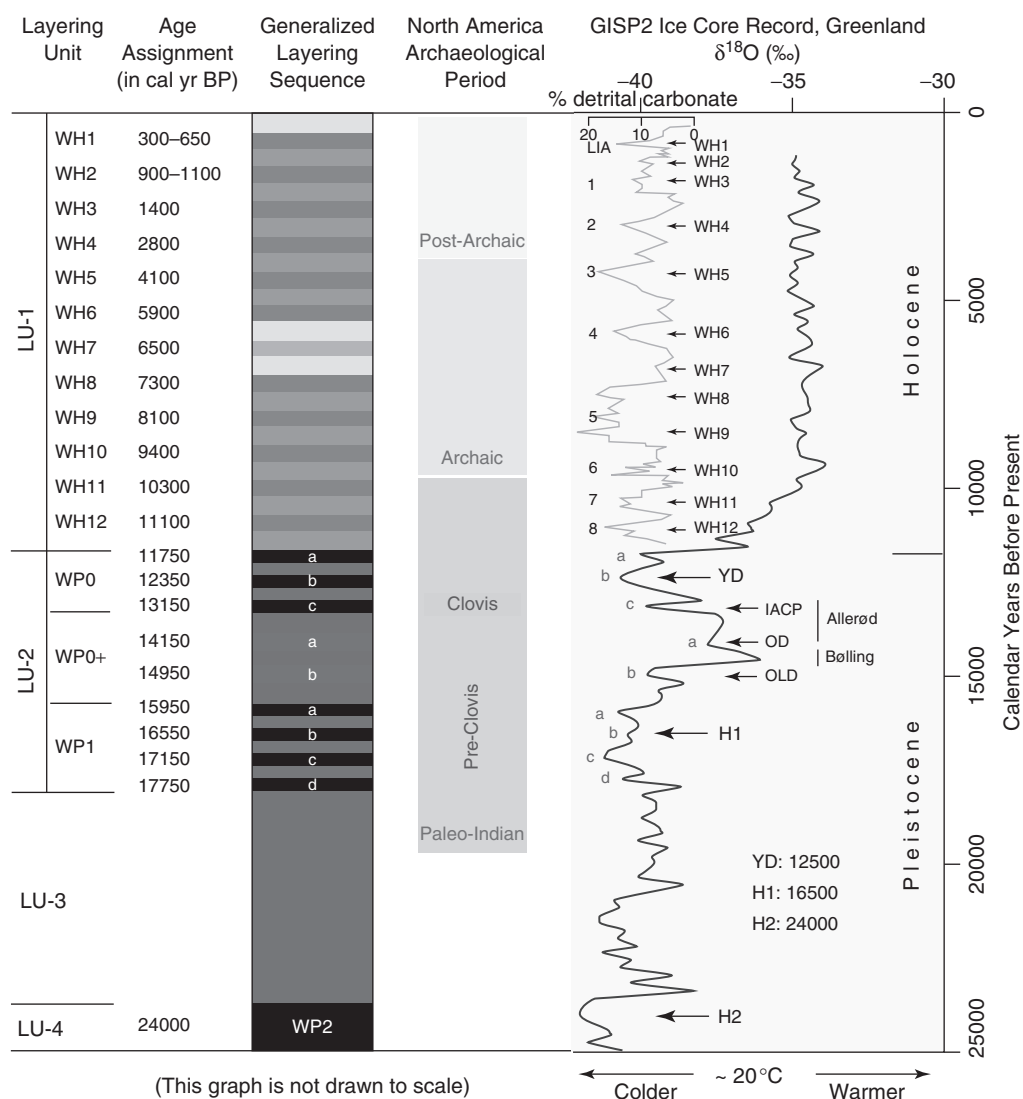


Figure 2 A generalized late glacial and Holocene varnish layering sequence in the drylands of the western United States and its climatic correlation with the GISP2 ice core record. Wet events recorded as dark layers (WP0a, WP0+a, WP0+b, WP1a–d) in the varnish-layering sequence correlate in time with cooling events represented by oxygen isotopic troughs (labeled a–c, a–b, a–d) in the GISP2 ice core record. Also included in this diagram is the climatic correlation of Holocene wet events (WH1–WH12) in the varnish record with Holocene cooling events (LIA, 1–8) in the North Atlantic deep-sea sediment records. Age assignments for dark layers in the varnish record are derived from the depicted climatic correlation (see Liu and Broecker 2007, 2008). The grayscale shading represents relative concentrations of Mn and Ba in varnish microstratigraphy. The North American archaeological periods or intervals are plotted against the varnish layering sequence for comparison: Post-Archaic (0–3 ka); Archaic (3–10 ka); Clovis (12.9–13.2 ka); Paleoindian (10–20 ka). LU = layering unit; WP = wet event in Pleistocene; WH = wet event in Holocene; H = Heinrich event; OLD = Oldest Dryas; IACP = Intra-Allerød Cold Period; YD = Younger Dryas; LIA = Little Ice Age.

fluctuations. The most prominent of such climatic oscillations are the Heinrich event H1, the Intra-Allerød Cold Period (IACP), the YD cold reversal, and Holocene millennial-scale cooling events. All these climatic oscillations happened nearly synchronously around the globe and left their imprints in various geological records such as polar ice cores, deep-sea sediments, and cave deposits and have been well dated by radiometric means. When spatially and temporally correlated, they provide accurate age references for the associated wetness variations archived in the varnish record (see Figure 2).

Application and limitation

Once radiometrically calibrated and climatically correlated, the master varnish layering sequence can be used as a correlative dating tool to estimate numerical ages for surface geoarchaeological features in drylands (Figure 3). In northern New Mexico, near a small town of Chili, a grinding stone (or metate) is coated with incipient spotty varnish (Figure 3a). The presence of numerous Anasazi pottery shards (Pueblo II–III pottery) at the sampling site indicates occupation of the place by the Anasazi Indians around 0.7–1.1 ka. Varnish from the metate displays a latest Holocene layering sequence of LU-1 (WH2) with basal dark layer WH2 (Figure 3b). Given the age scale of the master layering sequence established for the western United States (Figure 2), this yields a VML-based age estimate of 0.9–1.1 ka for the deposition of basal dark layer WH2. Since the WH2 deposition postdates the abandonment of the metate, the varnish age estimate suggests occupation of the site by the Anasazi Indians around 1.0–1.2 ka (assuming 100 years of varnish lag time), a result consistent with the pottery evidence. In the Mojave Desert of eastern California, a curvilinear petroglyph was pecked by ancient humans on a basaltic bedrock surface (Figure 3c). Varnish from the petroglyph grooves displays an early Holocene layering sequence of LU-1 (WH10), yielding a VML-based age estimate of 9.4 ka for the deposition of basal dark layer WH10, and thus 9.5 ka for the pecking event (Figure 3d). In Ocotillo of southern California, varnish from the flaked face of a primary core

displays a latest Pleistocene layering sequence of LU-2 (WP0a), yielding a VML-based age estimate of 11.75 ka for the deposition of basal dark layer WP0a and 11.85 ka for the flaking event (Figure 3e–f). This age estimate suggests occupation of Ocotillo by the Paleoindians during the terminal Pleistocene.

Like any other surface exposure dating techniques, VML dating has inherent limitations that hinder its chronometric application. First of all, VML dating relies largely on layering pattern interpretation of varnish microstratigraphy, which is experience-dependent and requires years of training and practice. Second, making varnish ultrathin sections plays a vital role in VML dating, which is also skill-dependent. Ultrathin sections that are well polished yield high-resolution images of varnish microstratigraphy, thus reducing ambiguities in layering pattern interpretation. Third, varying rates of varnish accretion over time create complexities in layering pattern interpretation. Fourth, not every varnish-filled microbasin contains a laminated microstratigraphy for layering pattern analysis. Large-grained and detritus-rich materials in varnish do not facilitate the formation of microlaminae. Postdepositional modifications such as chemical leaching and bioturbation may alter originally layered microstratigraphy. One simple way to avoid or minimize these uncertainties in VML dating is making three (or more if possible) varnish ultrathin sections for each sample and choosing the most unambiguous and oldest layering sequence for layering pattern interpretation and age estimate.

Conclusion

Although still experimental in nature, VML dating is a conservative age determination tool that yields minimum-limiting surface exposure ages for dated rocks. Laminated microstratigraphies exist in varnishes from warm and dry deserts of the world, including the Negev Desert of the Middle East, the Gobi Desert of western China and Mongolia, the Atacama Desert of South America, and the Sahara Desert of Africa. These desert regions host numerous sites of ancient petroglyphs, geoglyphs, and surface stone artifacts.

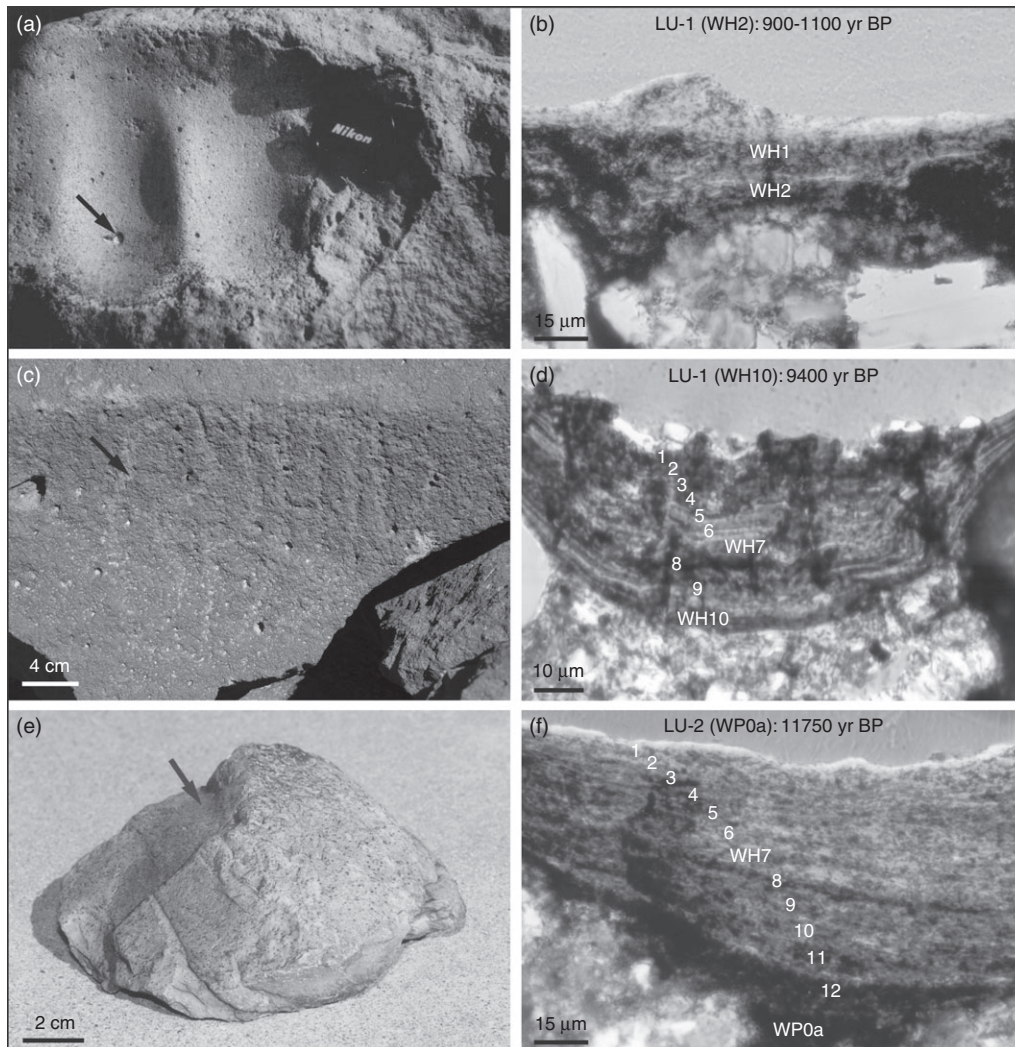


Figure 3 VML dating of petroglyph and stone artifacts in the drylands of western USA. *Upper panel:* A grinding stone is coated with incipient spotty varnish in northern New Mexico (a). Microstratigraphy in the varnish (b) displays a latest Holocene layering sequence of LU-1 (WH2), yielding a VML-based age estimate of 1.0–1.2 ka for site occupation by the Anasazi Indians. *Middle panel:* A curvilinear petroglyph is coated with patchy varnish in the Mojave Desert of eastern California (c). Microstratigraphy in the varnish (d) displays an early Holocene layering sequence of LU-1 (WH10), yielding an age estimate of 9.5 ka for the pecking event. *Lower panel:* A primary core is coated with well-developed patchy varnish in Ocotillo of southern California (e). Microstratigraphy in the varnish (f) displays a latest Pleistocene layering sequence of LU-2 (WP0a), yielding an age estimate of 11.85 ka for the flaking of this stone artifact by the Paleoindians. Arrows in the images point to spots where varnish-filled microbasins were cored with a mini-dremel for VML analysis.

Radiometric age calibration and climatic correlation of the varnish wetness records in the regions have been underway. Once they are completed, VML dating will have the potential of providing millennial-scale age estimates up to ~74 ka for surface geoarchaeological features in the world's deserts.

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Magnetostratigraphy

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Theory

Magnetostratigraphy deals with the recognition in a rock succession of the stratigraphic levels in which the polarity reversals of the Earth's magnetic field are recorded. Units of homogeneous (normal or reverse) polarity are called magneto-zones, while their correlative time intervals are called Chrons.

The Earth's magnetic field is generated in the outer core by the convection of electrically conducting liquid iron alloys driven by compositional and thermal buoyancy forces. These cause the fluid to rise or sink while being deflected by the Coriolis effect into helical structures that through magnetic induction continuously generate an essentially dipolar field (~90% of the total field) accompanied by nondipolar structures that vary over secular timescales. The geocentric dipole axis, when averaged over a few thousand years, becomes aligned along the Earth's rotation axis (Langereis et al. 2010).

The Earth's field possesses two polarity states, normal and reverse (Langereis et al. 2010, Figure 1), which can flip with no predicted periodicity. This random character confers stratigraphic value to magnetic polarity reversals. A reversal typically takes a few thousand years (or less) to occur, a process fast enough to generate globally synchronous time lines useful for correlating distant sedimentary or volcanic sequences. Dating is possible by correlating a magnetozone sequence to a radiometrically and/or astrochronologically dated geomagnetic polarity timescale (GPTS; see below). The polarity reversal frequency has increased from nil between 121 and 83 Ma in the Cretaceous (when the field maintained stable normal polarity) to around 5 per Ma over the course of the Cenozoic.

There exist natural processes that are able to register direction and intensity of the ancient geomagnetic field in rocks at the time of their formation. Rocks commonly contain magnetic minerals, for example magnetite and hematite. These minerals form in magmatic rocks by exsolution from solid solutions and acquire ferromagnetic properties upon cooling below their Curie temperatures (e.g., ~580 °C for magnetite). Once eroded and transported, they can also get incorporated in sediments by means of gravitational settling. Also, magnetotactic bacteria can biomineralize micrometric magnetite grains that can become incorporated in sediments. These magnetic minerals may be comprised of one or more magnetic domains, volumes characterized by an intrinsic magnetization at saturation. In the case of single domain grains, which typically carry a stable magnetization, this magnetic moment is aligned along preferred directions dictated by the grain shape or crystallographic axes.

During magma cooling to below the Curie temperature(s), or sedimentary settling of particles, these magnetic moments statistically align with the ambient geomagnetic field and are subsequently "locked" in the rock by further cooling or lithification processes, thus recording the direction of the field as thermoremanent magnetization (TRM) or detrital remanent magnetization (DRM), respectively. Post-depositional realignments of magnetic particles in the water-saturated topmost layer of the sediment can produce a post-depositional DRM. Compaction and dewatering then mechanically fixate the aligned particles, preserving the direction of the ambient field. A chemical remanent magnetization (CRM) is instead acquired when a magnetic mineral grows through a critical blocking volume at which the ambient field is again locked-in against thermal disorder. In all these cases, the generated primary magnetization can be stable for billions of years or until the rock is weathered or thermochemically altered, causing the original magnetization to be variably overprinted by a secondary magnetization.

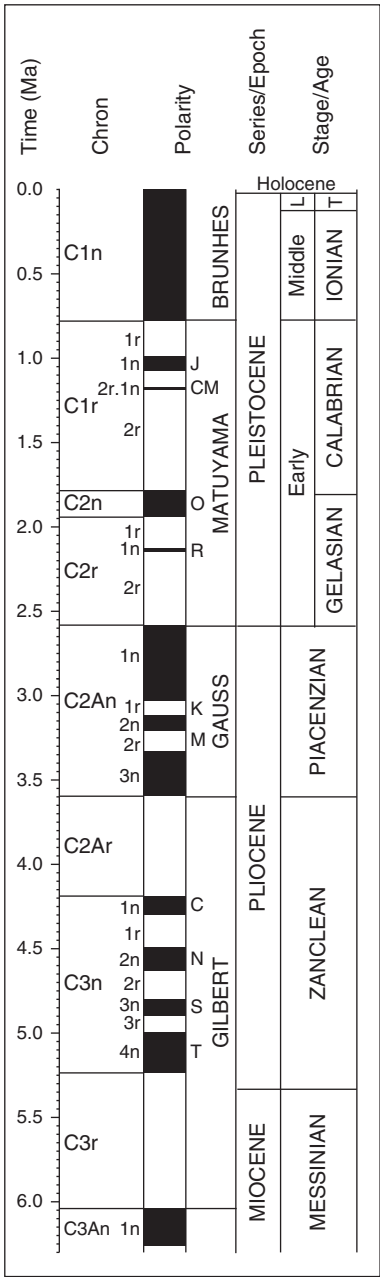


Figure 1 The Lourens et al. (2004) timescale (ATNTS2004) for the last 6 Ma tied to Pliocene–Pleistocene stages. Subchrons are as follows: J = Jaramillo; CM = Cobb Mountain; O = Olduvai; R = Reunion; K = Kaena; M = Mammoth; C = Cochiti; N = Nunivak; S = Sidufjall; T = Thvera (ages in main text and in Lourens et al. 2004). T = Tarantian; L = Late.

Methodology

Samples are taken in the field with an electric or gasoline-powered drill and oriented relative to the north and the horizontal plane with a magnetic or sun compass mounted on a specific orienting device. Core samples are then reduced to approximately 10-cc cylinders. Sampling can be performed also by inserting approximately 5-cc plastic boxes into oriented rock walls or by taking oriented blocks for subsequent sub-sampling. In the laboratory, samples are exposed to magnetic cleaning techniques that are able to define the magnetic component structure of the natural remanent magnetization (NRM). Cleaning is attained by exposing samples to either thermal or alternating magnetic field (AF) energy (Tauxe 2010). During thermal cleaning, samples are subjected to temperatures progressively increasing from room temperature to the Curie points of the constituent magnetic minerals, while during magnetic cleaning, to progressively increasing alternating fields up to the maximum coercivity of the magnetic minerals. The residual NRM is measured after each demagnetization step with a spinner or superconducting quantum interference device (SQUID) magnetometer, and the resultant variations in direction and intensity are visualized in so-called vector end-point demagnetization diagrams. Measurements are performed in a field-free space in order to limit the acquisition of spurious magnetic overprints. Magnetic component directions are extracted using least-square analysis on linear portions of the demagnetization diagrams. Standard Fisher statistics are used to calculate mean directions.

The most stable component of the NRM that can be isolated at high temperatures or AF fields is the characteristic remanent magnetization (ChRM), which is further investigated as a best candidate to represent the original (primary) magnetization acquired at the time of rock formation (as opposed to a secondary magnetization overprint, which is usually removed at lower temperatures or AF fields). This ChRM carries the magnetic polarity signal magnetostratigraphy is concerned with. Considering the northern hemisphere and excluding the effects of tectonic deformation or continental

drift, a ChRM directed to the north with positive (down-pointing) inclination is a record of normal polarity, while a ChRM directed to the south with negative (up-pointing) inclination is a record of reverse polarity.

Different rock magnetic experiments and reliability tests should accompany a magnetostratigraphic study. Experiments aim at determining the type of magnetic mineral(s) that carry the ChRM and their characteristics (grain size, domain state, etc.; Tauxe 2010). Reliability tests aim at constraining the age of acquisition of the ChRM. In a consistency test, the ChRM is considered primary when it defines a superposed sequence of magnetozones that can be laterally traced between distant sections and checked-upon by independent means (e.g., lithostratigraphy, biostratigraphy). A reversal test aims at determining the presence of residual and unresolved overprints by testing if the normal and reverse polarity component directions registered by the ChRM are antiparallel within statistical error (usually 95%). In a fold test, the ChRM directions from differently tilted beds of a cylindrical fold are compared on a stereographic projection before and after correction for the tilting of the strata: if after tilting correction they converge into a single distribution sharing the same mean direction, then this ChRM was acquired before tilting.

Timescales

Because magnetic polarity reversals occur aperiodically and are globally synchronous, they provide “bar code” patterns that can be used for correlations. When correlation is made to a geomagnetic polarity timescale, the numerical dating of a given rock sequence is also achieved. Various generations of timescales have been constructed over the years by integrating marine magnetic anomaly records with magnetostratigraphic, biostratigraphic, radiometric, and astrochronologic data from land sections and deep-sea cores (see Langereis et al. 2010). Classic timescales are those of Berggren et al. (1995) for the Cenozoic, and the astrochronological polarity timescale of Lourens et al. (2004) for the Neogene, while for

a recent summary of the Quaternary, see Ogg, Ogg, and Gradstein (2016).

In all these (and other) timescales, the youngest Chrons of predominant normal or reverse polarity straddling the last 6 Ma are named after leading geomagnetists: Brunhes, Matuyama, Gauss, and Gilbert (Figure 1). This sequence contains also magnetic polarity intervals of shorter duration called Subchrons, which are named after the locality where they were first observed (Jaramillo, Olduvai, etc.). A more formal classification also exists in which Chrons are prefixed by the letter “C” followed by a progressive number derived essentially from the correlative marine magnetic anomaly, complemented by the letter “n” or “r” indicating normal or reverse polarity; a final suffix may follow indicating Subchron subdivisions (Gee and Kent 2015). Examples are Brunhes Chron = C1n and Jaramillo Subchron = C1r.1n. The record of geomagnetic polarity reversal is known down to C34n (Cretaceous normal polarity Superchron, 83–120.6 Ma), then across the Jurassic and the Triassic, while for earlier times it is still largely incomplete (Ogg et al. 2016). There is also evidence of several magnetic polarity excursions of very short duration on the order of 3–6 kya (e.g., Mono Lake at 32 kya, Laschamp at 41 kya, Blake at 120 kya, Iceland Basin at 188 kya, Pringle Falls at 211 kya, Big Lost at 560–580 kya, Stage 17 at 690 kya, etc.; Laj and Channell 2015) that offer the potential of high resolution stratigraphy in the Quaternary, albeit their recording is frequently elusive in typically discontinuous continental records.

Key magnetic polarity reversal ages (Lourens et al. 2004) tied to Pliocene–Pleistocene stages (Ogg et al. 2016) that are relevant to archaeological studies (examples in Kukla and Nakagawa 1975; Parés and Perez-Gonzalez 1999; Laj et al. 2011) are shown in Figure 1 and are as follows:

- Base of Brunhes Chron (C1n) = 0.781 Ma (= Base of Middle Pleistocene).
- Top of Jaramillo Subchron (C1r.1n) = 0.988 Ma.
- Base of Jaramillo Subchron (C1r.1n) = 1.072 Ma.
- Top of Cobb Mountain Subchron (C1r.2r.1n) = 1.173 Ma.
- Base of Cobb Mountain Subchron (C1r.2r.1n) = 1.185 Ma.

- Top of Olduvai Subchron (C2n) = 1.778 Ma (~ Base of Calabrian).
- Base of Olduvai Subchron (C2n) = 1.945 Ma.
- Top of Reunion Subchron (C2r.1n) = 2.128 Ma.
- Base of Reunion Subchron (C2r.1n) = 2.148 Ma.
- Top of Gauss Chron (C2An) = 2.581 Ma (= Base of Quaternary/Pleistocene).

Alternative polarity reversal ages available in the literature may differ from those listed above by a few thousand years (e.g., ~0.773 Ma for the Base of the Brunhes; Channell et al. 2010; see also Singer 2014) depending on the dating method used.

Future directions

Among other topics, ongoing research is focused on (1) constraining the age of polarity reversals to within one precessional cycle, (2) confirming polarity excursions from multiple records, (3) integrating magnetostratigraphy with paleointensity data, and (4) retrieving magnetostratigraphic signals from samples with resistant overprints.

SEE ALSO: Archaeology; Archaeomagnetism; Dating in Archaeology; Magnetic Susceptibility

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Obsidian Hydration Dating

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Introduction and history

Obsidian hydration dating (OHD) is based on the fact that artifact manufacture exposes fresh, unweathered surfaces to the environment. Water from that environment then enters the glass by diffusion at a rate set by various factors, including the composition of the glass, the external temperature, and the relative humidity. If the appropriate diffusion coefficients are known, the depth of the diffusion can be correlated to the time over which the process occurred, that is, to the age of the artifact.

Archaeological interest in obsidian hydration began with the work of Friedman and Smith (1960). Friedman and co-workers concluded that the position of the hydration front could be fit to a quadratic equation with time, and modeled on Fick's Laws as:

$$x^2 = Dt \quad (1)$$

where x is the thickness of the hydration rim, D is the hydration rate, and t is time. Because the hydration rate is temperature dependent equation, (1) was combined with the Arrhenius equation, yielding:

$$x^2 = Ate^{-E/RT} \quad (2)$$

where A is a constant, E is the activation energy, R is the gas constant, and T is absolute temperature. Equation (1) is, however, a "rule of thumb" for diffusion modeling, not a solution to Fick's Laws, as it does not describe changes in water concentration with distance and time.

Unfortunately (see Anovitz et al. 1999), application of this work to archaeochronometry

has been plagued by both imprecision and inaccuracy. Anovitz et al. (1999) provided an example from the Chalco site in the Valley of Mexico that showed not only poor correlations with associated ^{14}C ages, but also significantly poor precision and accuracy. They showed this was, in part, due to the optical method used for analyzing the hydration depth in nearly all studies, and that the hydration profile (concentration with depth) observable using secondary ion mass spectrometry (SIMS) did not follow a simple error-function-like pattern, but was S-shaped, suggestive of a concentration-dependent diffusion mechanism. Experimental study of diffusion in Pachuca obsidian by Anovitz et al. (2004; 2006a) further showed that, even when reliable data were obtained, the penetration rate did not, necessarily, proceed as the square root of time.

Deviations from error-function solutions to Fick's Law are a function of the degree of structural change produced by the migrating species. As water is a network modifier in glass, and lowers its viscosity, the diffusion coefficient of water in glass should increase with increasing water concentration. Friedman et al. (1966) suggested that water concentration profiles in hydrated obsidian should be square or S-shaped.

The possibility of surface dissolution was also recognized as a potential problem for OHD. Friedman and Smith (1960) felt that it would be a problem only in rare instances. Efforts to correct for surface dissolution in archaeological samples have been limited to measuring hydration rinds in fissures located along the surfaces of artifacts.

In a series of papers using SIMS to measure hydration profiles, Anovitz and co-workers criticized standard approaches to OHD, suggested an alternative, and studied the rates and mechanisms of the hydration process. Anovitz et al. (1999) noted the consistent failure of traditional OHD to yield reliable results and attributed this to both the analytical methods employed and the mathematical description of the process. They also suggested that SIMS could be used to directly measure water concentration as a function of depth, provided examples for several

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types of glasses, and showed that reasonable fits to the hydration profiles could be obtained, except in the very near-surface region, using a compositionally dependent diffusion model. Riciputi et al. (2002) tested this approach using samples of Pachuca obsidian from the Chalco site in the Valley of Mexico for which good stratigraphically correlated ^{14}C dates were available. They developed a “characteristic point” approach whereby the complex diffusion profile could be characterized by a single depth, and showed that neither the traditional OHD equation for depth as a function of the square root of time nor a linear function fit the data. Rather, an excellent fit was obtained for a more generalized value ($\sim t^{0.75}$). They also showed that, using only two obsidian samples and their associated ^{14}C dates, a calibration curve could be derived that provides dates for other samples in excellent agreement with their associated ^{14}C dates. Finite difference modeling was also used to reproduce the shape of the hydrogen depth profile assuming concentration-dependent diffusion, and the dates obtained agreed well with associated ^{14}C ages. These results clearly indicated that, when empirically calibrated, hydration dating is feasible using SIMS, an approach they labeled ODDSIMS. Anovitz et al. (2004) presented experimental data on the hydration of Pachuca obsidian at 75°C for times ranging from 3 to 562 days, and compared these results with those from Chalco. They developed a technique for these experiments in which the samples were exposed to water vapor, rather than liquid water, with a chemical potential equal to that of the liquid at the pressure and temperature of the experiment, in order to reduce or eliminate uncertainties due to dissolution. Again, the results demonstrated that a simple square-root-of-time model was not adequate.

A key component of the work of Riciputi et al. (2002) was that the samples were locally calibrated, eliminating the effects of unknown local temperature patterns through time. Anovitz et al. (2006a) inverted this approach, combining an experimental calibration of the hydration rate of Pachuca obsidian as a function of temperature with the known ages of the samples to calculate integrated paleotemperatures as a function of time. Anovitz et al. (2006a) evaluated the effects of relative humidity on hydration rates and found that for relative humidity levels commonly

observed in most soils the effects on hydration dating should be relatively small.

Anovitz, Cole, and Fayek (2008) investigated the mechanisms of obsidian hydration. Comparisons between high- and low-temperature diffusion suggested that water concentrations in rhyolitic glasses hydrated at low temperatures are significantly greater than in those hydrated at high temperatures and low pressures. Surface concentrations, which equilibrate quickly with the surrounding environment at high temperature, change more slowly as temperature decreases, and may not equilibrate at room temperature for hundreds or thousands of years. A change in mechanism may be due to the inability of “self-stress,” caused by the in-diffusing species, to relax at lower temperature. These stresses may be greater than the tensile strength of the glass, and Fourier transform infrared spectroscopy (FTIR) analysis suggested the in-diffusing species was primarily molecular water. Anovitz, Cole, and Riciputi (2009) further investigated these processes by varying the isotopic composition of the in-diffusing water to determine whether a point-by-point analysis of the D/H or $^{18}\text{O}/^{16}\text{O}$ isotopic composition across the hydrated rim can be used as a paleoclimatic monitor. They found that both the isotopic composition of the waters of hydration, as well as that of intrinsic water from the initial glass formation vary dramatically during hydration, and a point-by-point paleoclimatic reconstruction is not feasible. However, once the glass is fully hydrated, and chemically driven diffusion is no longer occurring, isotopic reconstructions may be possible.

Techniques

Friedman and Smith (1960) noted that the hydration rim was visible under high-power magnification, and suggested that its width was dependent on time, chemical composition (obsidian source), and temperature. Based on their observations, three techniques utilize this concept to date obsidian.

Optical methods

Initial OHD work involved two optical methods. The empirical rate method correlates rim

widths with independent chronometric data (e.g., radiocarbon). The intrinsic dating method ratios rim widths to laboratory-determined hydration rates. The latter directly dates obsidian artifacts, is simple, rapid, and inexpensive (it uses an optical microscope), and allows a large number of chronometric determinations to be obtained from a single site. Unfortunately, consistently reliable results have not been achieved using this method because of two factors: (1) the inherent imprecision in any measurement done using visible light (i.e., errors inherent in optical measurement of hydration rim thickness), and (2) the formation of the Becke line (a bright line that occurs in thin sections at the boundary between two materials with different refractive indices, whose position is focus-dependent (Anovitz et al. 1999). In addition, the rim is clearly gradational (Figure 1).

Secondary ion mass spectrometry (SIMS)

As a consequence of the inaccuracy associated with optical OHD, Anovitz et al. (1999) developed a new approach using SIMS. They showed that the shape of the water profile is inconsistent with that predicted using current OHD equations, indicating that the theoretical basis for OHD is flawed.

SIMS is an excellent method for obtaining high-precision information on the concentration of water as a function of depth, and therefore is an ideal technique to investigate the process of obsidian hydration. When utilized in depth-profiling mode, SIMS can resolve concentration variations over a few nanometers for a wide variety of elements, over depths ranging from tens of nanometers to several microns. SIMS is based on analysis of ions ejected from a sample during bombardment by a focused beam of primary ions accelerated at 2–20 keV. The composition of these secondary ions is representative of the composition of the sputtered surface, so a mass spectrometric analysis provides a quantitative elemental or isotopic analysis of the sputtered volume. Depth resolution is typically in the 0.02–0.04 μm range, although the instrument can be adjusted to obtain much finer resolution (Anovitz et al.

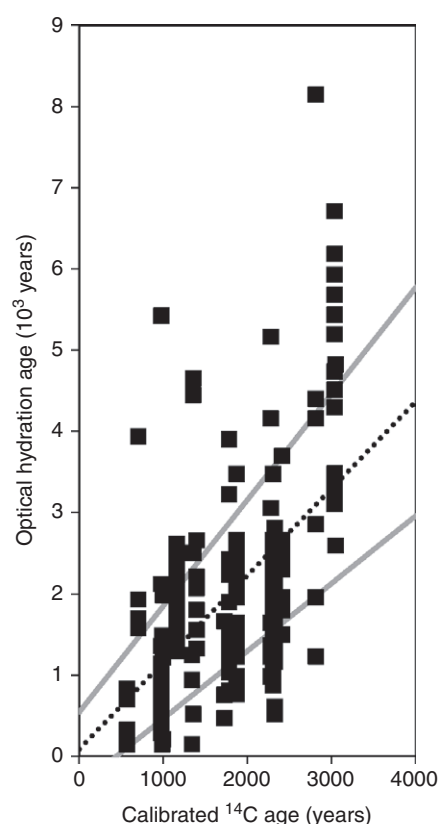


Figure 1 Typical hydration rim on a 180,000-year-old obsidian tool from Gademotta Ridge, Ethiopia. Presence of a significant stress field is apparent in thin sections of hydrated obsidian, as hydrated regions are optically anisotropic. Crossed polars, 1 λ accessory plate, figure width = 0.125 mm.

Source: Reproduced with permission from Anovitz (1999). © Elsevier.

1999). Although this ODDSIMS technique provides several advantages over the optical method (e.g., shape of hydrogen profile, accurate and precise results independent of the analyst), there are several disadvantages. These include (1) cost of analysis; (2) diffusion rates are compositionally dependent and, therefore, diffusion experiments on obsidians with compositions similar to the artifacts are required to develop calibration curves. This is time consuming and expensive; and (3) local calibration curves, similar to those developed by Riciputi et al. (2002),

require samples with well-defined ^{14}C ages. This renders ODDSIMS an empirical rate dating method, rather than a stand-alone intrinsic dating method.

Liritzis (2006) published a SIMS study of obsidian from several sites in Greece, the United States, and Mexico, where he took into consideration the surface saturation (SS) layer and dubbed his method SIMS-SS. This is based on Fick's Law, and relates concentration to hydration depth. It incorporates the surface saturation layer and equations that describe the diffusion rate. The diffusion coefficient is assumed to vary exponentially and is derived from the first derivative of the diffusion profile. Liritzis (2006) argues that the SS layer forms relatively quickly and there is no true time-dependence of the surface concentration, which contradicts the results of Anovitz et al. (2004) which show increasing near-surface concentration of hydrogen with time. SIMS-SS results are not, however, based on controlled, experimentally derived data, but on archaeological artifacts, and do not take into consideration the chemical composition of the material examined.

Infrared spectroscopy

Stevenson and Novak (2011) used infrared transmission spectroscopy to study molecular water diffusion in experimental obsidian samples at low temperatures (90–190 °C). The obsidian samples varied significantly in the concentration of structural water within the unhydrated material. Long-term (60–360 days) hydration sequences at 90 °C showed a $t^{0.6}$ time dependence for the uptake of molecular water forming the hydration layer. The structural water concentration of the unhydrated bulk obsidian is highly correlated with the pre-exponential coefficient and activation energy and may be used to estimate Arrhenius constants to determine obsidian hydration rates at ambient temperature (i.e., develop calibration curves for archaeological artifacts). The advantage of this approach is its ability to estimate rates of water diffusion based upon glass composition. In addition, it can estimate rates of diffusion for individual artifacts rather than using a generalized composition for geological sources or flows from

which the artifact originated. The disadvantage is that it is destructive. Development of calibration curves requires preparation of polished slabs cut from the artifact. Similarly, hydration rim measurements require that the hydrated surface is separated from the rest of the sample. Sample preparation techniques are very exacting and can destroy the entire sample, limiting the number of samples dated.

To avoid some of these issues, Stevenson, Lade-foged, and Novak (2013) investigated infrared photoacoustic detection. This method measures water in solids based upon the thermal response to infrared heating. Although it is also destructive, it requires less tedious sample preparation and has the ability of analyzing opaque obsidians. They applied this method to artifacts recovered from Rapa Nui (Easter Island), and were able to correlate the ages they obtained using infrared photoacoustic detection with ages obtained using accelerator mass spectrometry (AMS).

Future prospects

In their initial paper on the subject, Anovitz et al. (1999) labeled OHD, as it was then known, a failure. The demonstrated poor precision and/or accuracy of optical techniques continue to justify the original conclusion. However, available evidence suggests that, in modified form, obsidian hydration dating may remain useful. At least two criteria must be met. First, accurate measurements of the extent of hydration must be obtained. SIMS provides such an analytical approach. While, in our estimation, a definitive demonstration is not yet available for the FTIR technique, this approach of Stevenson has significant promise.

The second limitation is calibration. Even where experiments (e.g., Anovitz et al. 2006a) provide a careful, polythermal, calibration of hydration rates, significant difficulties must be addressed. First, such calibrations are extremely time consuming, and thus unlikely to be available for many sources. Second, because diffusion of water into obsidian is temperature dependent, calculations based on an externally calibrated hydration rate depend on determination of hydration temperature. This value cannot be known, a

priori, unless local variations in paleoclimate are known over the entire burial history of the artifact in question. Thus, the best solution is likely to use OHD as a secondary technique, calibrating local rates relative to other approaches such as ^{14}C . As a final caveat, however, it is by no means certain that obsidians from all flows, or even parts of a given flow, from a given source hydrate at the same rate, and thus the utility of this modified approach remains to be further tested.

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SEE ALSO: Archaeological Sciences; Archaeometry; Chemistry in Archaeology; Climate Change and Dating; Dating (Burnt) Lithics; Dating in Archaeology; Deterioration of Vitreous Materials; Geoarchaeology; Glass and Faience; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Infrared Reflectance Spectroscopy; Isotopes; Mass Spectrometry (MS); Paleoenvironmental Reconstruction; Radiocarbon Calibration and Age Estimation; Vibrational Spectroscopies

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Quaternary Large-Mammal Zones

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Background

A rock unit, characterized by the occurrence of fossils of a particular species or a combination of species, is called a biozone and the time in which these organisms lived is called a biochron. A sequence of biozones is called a biozonation and gives the “relative” ages of the biozones to each other (“older/younger than,” etc.). Biozones may be based on many kinds of organisms, including large and small mammals. The Quaternary corresponds to the past 2.6 million years of the Earth’s history. This is close to the maximum age of the archaeological objects that are known. The branch of science that uses biozones to study the relative ages of strata is called biostratigraphy and has been the main method to compare ages in geological and archaeological contexts, and it still is, when physical methods cannot be applied. If such methods, like uranium series and electron spin resonance dating, or paleomagnetism have been used to date the biozones, we know their “absolute” age, expressed in thousands or millions of years (kya or Ma, respectively).

Historical development

The notion that there had been different periods with different species of animals became widespread in the eighteenth century. Around the turn of the century, it was known that different geological formations were characterized by different fossil contents, representing different periods, and this information was used to produce geological maps by William Smith in Britain and Georges Cuvier and Alexandre Brongniart in France. This is the beginning of biostratigraphy.

By this time, it was known that species could go extinct and to some extent that new ones might originate: Lamarck and Darwin published their theories on evolution in 1809 and 1859, respectively.

In the middle of the nineteenth century, d’Orbigny and Oppel were among the first to use the term “zone,” either for a rock unit or time unit, characterized by fossils of certain organisms. Zones are the smallest stratigraphic units. The first edition of the *International Stratigraphic Guide* (Hedberg 1976) considered a zone to be a body of strata with a particular content, limited by diachronous borders, while the corresponding chronozone is the total time range of this content. This content can be fossils (biozone), lithology (lithozones), minerals, and so on. The fossil content that defines a biozone can be the total range of a taxon (species, genus, etc.), the coincidence of two or more taxa, the presence of one taxon and the absence of another, the particular abundance of a taxon, and so on. A biozone is usually named after the defining taxon or taxa, but if the zone is part of a sequence, it is often numbered. A taxon may appear suddenly or it may gradually spread into a geographic area. If such a taxon is used to define the boundaries of a biozone, the boundary will be synchronous in the first case and in the second it will be diachronous. The corresponding chronozone or biochron covers the total time range from the first till the last appearance.

Practical constraints to large mammal zones

Biozonations are affected by the different sedimentary environments with different potentials for the preservation of fossils. In the deeper parts of the seas, thin clay layers may incorporate abundant microfossils, allowing for a precise study of biological change. By contrast, on the continents, erosion prevails and sedimentation is patchier, both in time and space. As a result, continental long continuous sedimentary sequences are much less common than marine

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ones. Continental biozonations are often based on pollen or the remains of mammals. Fluvio-lacustrine environments and caves tend to have the best fossilization potential for mammals, but are prone to have hiatuses. Microfossils may be evenly distributed in fine sediments, while concentrations of mammal fossils are usually hard to find, especially of large mammals. While soaking and sieving a small piece of marine clay may rapidly yield a nice collection of foraminifera, collecting small mammals is more time consuming and the excavation of a large mammal locality often takes several years and is usually done by a team. These practical differences lead to differences in biostratigraphical procedures and even to separate large and small mammal biozonations, even though there are many localities where both occur together. There has been much discussion on the methodology to be followed in mammalian biostratigraphy, whether type sections should be used, whether the best faunal criterion for boundaries was dispersal events or evolutionary “steps,” and so on.

In Europe, there tends to be much vegetation, the geological strata cannot be easily seen as in arid landscapes, and there is a long tradition to excavate known fossil localities. As a result, the ages of these localities (or their fossil associations) are compared, rather than the ages of geological strata. This custom developed into biostratigraphic schemes in which reference localities (often from quite different areas) are placed in a supposed chronological order. Nearly none of the presently used mammal biozonations for the European Quaternary, Neogene, or Paleogene follows strictly the International Stratigraphic Guide, and many stratigraphers do not even consider them to be biozones, but call them simply “units.”

Biozonations based on large mammals are attractive for the study of prehistory, since one of the indications of human activity is bone accumulations due to hunting. Large mammal zonations have been proposed for most continents, but in some, human presence (and thus archaeology) is well within the range of C^{14} dating and younger than most or all recognized biozones. The latter is the case in Australia and the Americas. In Asia, where there is either insufficient detail or no biozones have been formally defined that cover human presence.

Relevant large mammal biozonations

Azzaroli (1967) divided the Villafranchian into what he called the lower, middle, and upper zones, which corresponded to sub-stages of previous authors. Later he recognized five “faunal zones” or units. This developed into a scheme with 13 faunal units covering the Quaternary (Gliozzi et al. 1997) (Figure 1). No boundaries were defined, but the scheme is accompanied by a range chart, where the entries and exits of the taxa are indicated. Each unit is called after a reference locality, nearly all of them Italian. Notwithstanding, the scheme is used also outside Italy.

Guérin (1982) defined the MNQ (Mammal Neogene Quaternary) units as an extension of the previously existing MN units for the European and circum-Mediterranean Neogene and continued the numbering. There have been several updates (e.g., Faure and Guérin 1992). Twelve units, MNQ 16–27, correspond to the Quaternary. Each of these units is defined with a variety of criteria: characteristic stages of several evolutionary lineages, several “typical” associations of two taxa, several first appearances. Most importance is given to rhinoceroses and other large mammals, but also small mammals are used.

The MmQ biozones were defined on the basis of small mammals, but include as additional information many large mammals (Agustí, Moyà-Solà, and Pons-Moyà 1987), and have been used by others working on large mammals.

Coppens (1972) introduced a biozonation or biostratigraphic scheme for Africa, of which zones I–IV correspond to the Quaternary. Based on the evolutionary stages of lineages in the Suidae and Elephantidae, Maglio (1972) recognized three biozones, which were modified by Harris (1983). These are true biozones, based on rock sequences with their fossil contents. They cover the period between some 3 and 1 Ma.

The future of biozonations

Many of the East African deposits are well dated because of the widespread tuffs, so that the ages tend to be given directly and the use of biozones is now largely abandoned. In Europe, it does

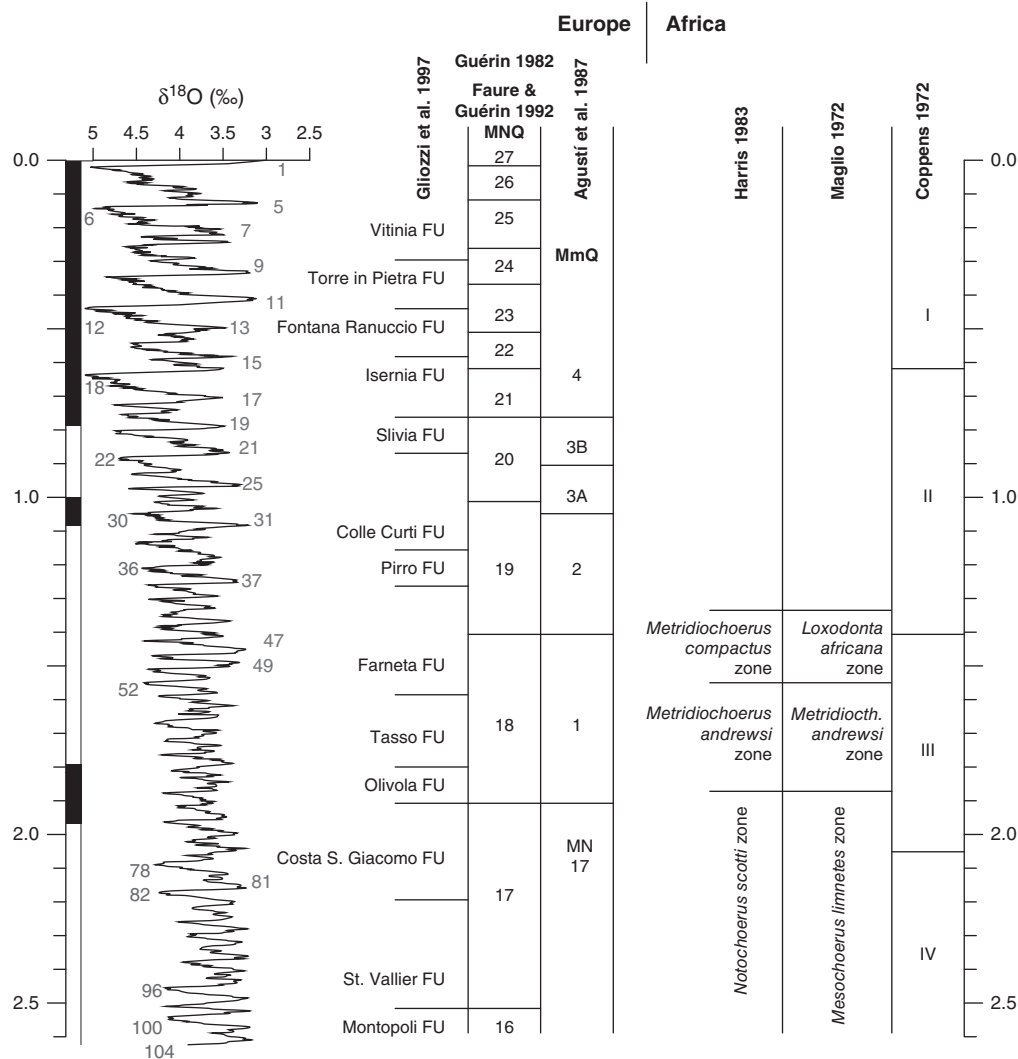


Figure 1 The main large mammal zones of the Quaternary of Europe and Africa. Ages are approximate and the position relative to oxygen isotope stages follows Gliozzi et al. (1997).

not seem likely that in the near future, physical methods of dating will replace biostratigraphy. However, all of the biozones or units were defined a long time ago. Research on the evolution of the large mammals has proceeded and present taxonomy is often not in accordance with the information on which the biozones were based. In any case, by now more precision is wanted. The average duration of the Italian faunal units, the MNQ, and MmQ zones is around 200, 217, and 325 kya, respectively. However, for the European Middle Pleistocene one would like enough

precision to recognize the major climatic cycles (with an average duration of about 100 kya) and correlate to the marine oxygen isotope stages. Another problem is the accuracy of the biozonations. Either no specific boundary criteria were given, or several, which, occasionally, with the present state of knowledge, correspond to different climatic cycles or to the warm and cold phases of a single cycle.

For biostratigraphy to continue to be a useful tool in prehistory and geology, more precise biozones should be defined. Middle and Late

Pleistocene zones should aim to recognize at least the glacial and interglacial phases of each major climatic cycle, which means an average duration of about 50 kya. It might prove to be difficult to recognize each of the glacial phases, since their faunas tend to be less known, but such a precision should be possible for the interglacial phases. Each boundary should be precisely defined by a single criterion, while additional criteria should be used, recognizing their lesser value in case of conflict. The validity of the definitions of the units should be regularly evaluated and compared to other information on the ages of the localities.

SEE ALSO: Dating and Electron Spin Resonance (ESR); Magnetostratigraphy; Quaternary Micro-Mammal Zones; Uranium-Series

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Quaternary Micro-Mammal Zones

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Introduction

The archaeological and paleontological histories during the Quaternary need a fine, accurate, and global time framework, that is, a Quaternary timescale. A time-based framework allows us to view the entire system, including sites, taphonomy, paleoecology, sequences, and cultural and biological (paleontological) evolution, rather than considering only individual circumstances. Relative dating using the fossil content follows the geological principle of faunal succession of William Smith (England, 1700s), who noticed that the species—namely “*kinds of fossils*” in the 1700s—change through a vertical succession of strata, and also that the same vertical changes in fossils occurred in different places. Using the fossils collected from rocks in one part, it is possible to predict the succession of rocks and fossils in other parts. This is known as the biostratigraphic correlation. The use of fossils to determine the age of rocks is based on the fact that organisms change permanently in a progressive and irreversible evolutionary process. For this reason, geologic time can be divided into successive intervals, or zones, characterized by associations of fossils in each zone. There are different ways of subdividing the strata in biostratigraphic zones; that is, there are different types of biozones. They may be defined on the basis of a single taxon or associations of taxa, relative abundances of taxa, or variations in features related to the distribution of fossils (see “Taxonomy” below). The usual limits of a biozone are based on the first and/or last appearance datum/occurrence of taxa (FAD, LAD). The biozones are made conventionally after studying different stratigraphic sections. The rules, nature, and more details about the biostratigraphic units

can be read in the Stratigraphic Guide of the International Commission on Stratigraphy.

Biozonation based on micromammals

Biozonation based on macromammalian assemblages has long served as a biostratigraphic framework in several places (see QUATERNARY LARGE-MAMMAL ZONES). Biostratigraphy is also acquiring high precision when used with micromammals in archaeological and/or paleontological sites (Cuenca-Bescós et al. 2010, 2016a, 2016b; Maul and Markova, 2007; Repenning 2003; Kawamura and Zhang 2009). Relative dating and constructing time in archaeology is based mostly on micromammalian zones because ideal taxa for biozones are those with abundant fossils, which show good preservation of the diagnostic characters in the fossil record, and rapid evolution of their species. These three conditions are achieved with micromammals. During the Quaternary, the abundance and rapid evolution of certain lineages of lagomorphs, rodents, and insectivores make these groups the best tools for biostratigraphy and biochronology. Recent quantitative methods applied to biochronological correlation with small mammals have improved the resolution of the biochronological time framework (Cuenca-Bescós et al. 2016a, 2016b; Galster, Guex, and Hammer 2010). The reason is that their teeth are accumulated in great numbers in archaeological sites. The isolated teeth are composed of very hard skeletal tissues and are diagnostic in their taxonomic classification. Moreover, paleontological studies of rodents show that they are mammals with fast evolutionary rates (Bininda-Emonds 2007). A good example is the evolution of the faunal succession during the Early Pleistocene in the archaeological and paleontological sites from the Trincheras del Ferrocarril in Atapuerca: In nearly half a million years the micromammals’ associations change completely; during this interval, there is the LAD of 12 species and the FAD of 13 (Cuenca-Bescós et al. 2010, Figures 4 and 5).

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Archaeological site and digging of micromammals

Microvertebrates in general are not encountered through standard excavating methods, and specialized recovery techniques are generally required to obtain such taxa. Techniques include washing and sieving sediments, and once the sediments have been washed off, we obtain fine and coarse concentrates. These are spread thinly and evenly in a sorting tray that is marked with a grid system, and then fossils are removed with fine forceps and the naked eye or optical devices (Cifelli, Madsen, and Larson 1996).

Taxonomy

In taxonomy, the taxon (plural taxa) is the systematic categorization of any fossil or living organism, such as phylum, order, family, genus, or species, though the basic unit for biozonation

is the species. Classification of the species is based on the identification of the diagnostic characters in the fossil teeth, usually the first lower molar in several groups of rodents, and the mandible and postcranial elements in insectivores and bats (Cuenca-Bescós et al. 2010, 2016a).

Micromammalian zones during the Pleistocene

The Pleistocene is a time span that represents important faunal turnovers. Evolution of faunas and biostratigraphy of the continental Pleistocene have in general faced the problem of being based on isolated sites and on short and mostly discontinuous sequences. The search for good and complete stratigraphic sequences to analyze micromammalian changes through the vertical succession of strata have been the main concern of paleontologists all over the world.

Period	Epoch/Age		Ma		Tent. North West Eu Stages	Spanish sites	UA
Quaternary	Holocene		0-0.012			El Mirón ++yac cantabrico Caldas da Rainha, Castro de Zambujal, Cova de Bolumini 21-12, Colomera Asup., Colomera EE1, Valdavara 1 level H, Cova de les Cendres Holoceno, Cueva de la Buena Pinta H, Cova Fosca N.A., Colomera CE12, 13, 14, Cova Fosca M. ++	8&9
	Late Pleistocene	Tarantian	0.012-0.13	Toringian	Saalian	Portalon, Galeria de las Estatuas, El Mirón Sidrón ++yac cantabrico Cobrante Tafesa Valle del Jarama, Preresca, Cova de les Cendres III-I, Colomera CE15, Gorham's Cave III, Cova Fosca E., Cova de Bolumini 28-32, Cova de les Cendres XIV-XVI-C, Gorham's Cave IV, Cova de les Malladetes, Gruta da Figueira Brava, Ibex Cave, Gabasa G, D, Aguilón, Cueva de la Carigüela, Abric Romani Nivel D, J, N, O, Cueva de la Buena Pinta, Navalmaillo, Cova del Gegant, Mule, Camino, El Higuero, Cueva del Agua, Arganda ++	7
	Middle Pleistocene	Ionian	0.13-0.78		Elsterian Early Brunhes Arvicola faunas	Sima de los Huesos, Sima del Elefante 18,19, Galeria GII, GIII, Gran Dolina 10, 11, Cueva del Agua, Cullar de Baza, 1, Ambrona, Aridos 1, Cuarterones, Villacastín, Galeria Pesada	6 4&5
	Early Pleistocene	Calabrian	0.78-1.80		Cromerian Early Brunhes Mimomys Faunas	Gran Dolina 8	3
						Gran Dolina 6, 7	
					Bavelian	Cullar de Baza C, Gran Dolina 3-5, Puerto Lobo 1, 4, Huéscar 1*, Vallparadis, Cal Guardiola, Chaparral, Huétor Tajar, Tojaire	2
					Eburonian-Waalian	Cueva Victoria 1a, 1b, II, Fuente Nueva 3, Barranco León 3, 5, Orce 3, Cortes de Baza, 88, Sima del Elefante 7-14, Bagur 2, Loma Quemada 1, Muntanyeta dels Sants de la Pedra, Venta Micena, Orce 4, 5, 6, 7, Cañada de Murcia 1,2, Quibas, Almenara-Casablanca 3	1
					Gelasian-Tiglian Pretiglian	Incarcal, Alqueria, Zújar 14, Galera 2, G, H, Tollo de Chiclana 10, 10B, Cortes de Baza 01, 41, 3, Orce 2, 7, D, C, Venta Micena, Barranco Conejos, Fanelas P-1, Almenara-Casablanca 1, Islas Medas, Cañada Real, Valdeganga 7(=VL III), 10 Alloxaina? Galera 2, Fuente Nueva 1, Fuentecilla 2,5?, Cementerio de Orce B, Cortijo D. Alfonso, Cortijo D. Diego	
					Reuverian	Tollo de Chiclana niveles inferiores a TC10&10B, Zújar, Cañada de Murcia 3	
	Neogene	Pliocene	Piacenzian	older			

Figure 1 Biostratigraphic correlation chart for Quaternary sites of Spain and north-west Europe based on small mammal assemblages from selected localities (modified from Cuenca-Bescós et al. 2016a). UA, Unitarian associations.

Biozones & significant species	Atapuerca FU	Radiometric ages Ma	Europe	FAD/LAD
Present day fauna	9	0.00	Present	
<i>Terricola lusitanicus</i>	8	0.003–0.0026 0.125	Holocene	F <i>I. cabreræ</i>
<i>Iberomys cabreræ</i>	7		Late Pleistocene	
<i>Clethrionomys glareolus</i>	6c		<i>Clethrionomys glareolus</i>	F <i>C. glareolus</i>
Unnamed	6b	0.240 0.313	Middle Pleistocene fauna	
<i>Iberomys mediterraneus</i> —middle Ple Homo	6a	0.337–0.418 0.434	Cromerian Complex	F <i>I. mediterraneus</i> , <i>Arvicola</i> cf. <i>sapidus</i>
<i>Microtus ratticepoides</i>	5b	0.611	Bavelian / Early Cromerian	L <i>Mimomys savini</i>
Unnamed	5a	0.780		L <i>D. glyphodon</i> , <i>S. gregaloides</i>
	4			
<i>Victoriamys chalinei</i> FAD and LAD of <i>Homo antecessor</i>	3	0.851–0.833	Villafranchian/ Epivillafranchian transition	F , LV. <i>chalinei</i> , F <i>Mimomys</i>
<i>Allophaiomys lavocati</i> (First Appearance <i>Homo</i> sp. Ple Eu)	2			
	1	1.2	Villafranchian Pirro Nord Colle Curti	L <i>Allophaiomys</i> species, <i>Castillomys</i> species

Figure 2 Biochronology and biozone boundaries of the Quaternary in Europe based on FAD and LAD of small mammal species.

Western Europe

In western Europe, there are the sequences of Kozarnika Cave (Bulgaria), Kärlich (Germany), and Zújar and Atapuerca (Spain). The continuous archaeological and paleontological record in the Sierra de Atapuerca caves, which contain the most extraordinary accumulation of evidence of human evolution in Europe, ranging nearly continuously from the Early Pleistocene to the Late Pleistocene and Holocene, and with its abundant micromammalian fossil record, offers the possibility of recognizing faunal replacements, dating their numerical age, establishing a stratigraphic range of faunal associations, and correlating them with reference localities in Europe (Cuenca-Bescós et al. 2010, 2016a, 2016b).

The evolution of several lineages of micromammals and the succession of faunal events, such as the FAD and LAD pertaining to important fossil markers, which can be calibrated with magnetostratigraphic and radiometric data, permit the definition of biozones (or faunal units

(FU)). An update of the European microfauna has been published in a volume devoted to the biochronology, biostratigraphy, and paleoecology of small vertebrates from archaeological and paleontological sites in Cuenca-Bescós et al. (2016b). The biostratigraphy of the Quaternary of Europe based on small mammals has a long tradition, with the works of Major, Hinton, and Cuvier, and during the twentieth century when several authors contributed to the European biozonation, such as Agustí, Chaline, Kotsakis, Markova, Mein, van der Meulen, Nadachowski, Heinrich, Kowalski, Fejfar, Sala, and Tesakov—a foundation that we can only improve by going through the taxonomy and paleobiology of small mammals using new techniques such as scanning electron microscopy, computed tomography, biomechanical, biomineral, histological, and ultrastructural studies, and by using statistical methods. A proposed biostratigraphic correlation for the Quaternary sites of Spain with micromammals is shown in Figure 1.

Central and eastern Europe

Among rodents, arvicolines are the best micromammalian tools for biostratigraphy (Fejfar, Heinrich, and Kordos 2011). Maul and Markova (2007) provide an interesting and critical overview of the biozonation in central and eastern Europe based on these rodents. As in the example provided for western Europe, the authors suggest a good number of stratigraphic sections and localities and provide a chart of the micromammalian zones in central and eastern Europe (Figure 2).

Asia

Biostratigraphic correlation between Europe and Asia has been made almost exclusively using micromammals, especially rodents, which show rapid dispersals from northern Asia to China. Studies of fossil ochotonids and arvicolines related to archaeological and paleontological sites are gaining relevance, especially after new discoveries of archaeological localities in the Baikal region in Russia and in China (Erbajeva and Alexeeva 2013; Kawamura and Zhang 2009).

North America

As in Asia, the primary biochronologic controls are the brief periods of rapidly spreading or dispersal events of rodent faunas (mainly arvicoline, or microtine for American authors). Repenning shows that the micromammalian zones build with arvicoline rodents to provide a nearly complete correlation of Pleistocene events throughout most of Holarctica, from the Early Pleistocene to the oldest of 14C dates. The dispersal events apparently occurred near the ends of episodes of most extensive grasslands (Repenning 2003).

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Radiation Exposure and Dating

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The cosmogenic nuclides

Cosmic-ray particles impinge continuously and isotropically (invariant with respect to direction) onto the Earth's atmosphere, in which they dissipate their energy efficiently through nuclear reactions, leaving cosmogenic nuclides as residues. The flux and energy of the primary and secondary particles (primarily neutrons) produced in the nuclear cascades thus exponentially decrease as a function of the thickness of atmosphere crossed, and only about 0.1% of them reach sea-level with enough energy to induce nuclear reactions in the Earth's crust (in-situ production). While in the atmosphere the production rate of cosmogenic nuclides exponentially increases with altitude, in the Earth's crust, it exponentially decreases with depth. Currently, the cosmogenic nuclides most used in archaeological sciences are ^{10}Be , ^{26}Al , and ^{36}Cl .

The accelerator mass spectrometry (AMS)

The mode of production of the cosmogenic nuclides implies they are rare in natural environments. Comparatively, isotopes (same atomic number but different mass number) and isobars (same mass number but different atomic number) of these cosmogenic nuclides are overwhelmingly abundant. Thus, the concentration of the stable ^9Be isotope and of the isobaric boron (^{10}B) is at least 10^8 times higher than that of ^{10}Be , which prohibits the use of the mass spectrometry technique whose level of separation cannot exceed 10^5 – 10^6 . It is the same for ^{26}Al , whose atmospheric production rate is 250 times lower than

that of ^{10}Be and whose stable isotope, ^{27}Al , is naturally abundant ($^{26}\text{Al}/^{27}\text{Al} \sim 10^{-14}$ – 10^{-15}). For ^{36}Cl , the abundance ratios $^{36}\text{Cl}/\text{Cl}$ are between 10^{-12} and 2×10^{-14} . Counting radioactive decay also poses serious technical problems. The ^{10}Be production rate in the atmosphere being about 100 times smaller and its half-life 300 times longer than that of ^{14}C , the activity of ^{10}Be is about 3×10^4 lower than that of ^{14}C , with that of ^{26}Al and ^{36}Cl being, respectively, about 3×10^6 and 3×10^5 times lower.

The necessity of fully exploiting the potential of the cosmogenic nuclides ^{10}Be , ^{26}Al and ^{36}Cl , by lowering the detection limit to a few hundred thousand atoms, led to the development of the AMS technique. To unambiguously identify, detect, and finally count the number of atoms of interest, we must have access to both to the mass number and the atomic number. For a given energy, the mass number corresponds to a specific radius of curvature in a given magnetic field (Lorentz force). Also the atomic number corresponds to a specific energy loss in a given material thickness (Bethe-Bloch law). The use of the unique characteristic of the energy loss in a thin material thickness followed by the detection/characterization in a suitable detector is possible only if the atom of interest has an energy high enough to allow both steps to be performed sequentially. Therefore, very schematically, the AMS technique inserts an acceleration stage between the injection and the analysis section of a conventional mass spectrometer.

Atmospherically produced cosmogenic nuclides

Given its production from the two most abundant constituents of the atmosphere (nitrogen and oxygen), and its long half-life (1.387 ± 0.012 million years (Ma)) allowing dating over ~ 10 Ma, ^{10}Be appears as a powerful dating tool.

Once produced in the atmosphere, ^{10}Be is oxidized. Then it attaches to aerosols and is introduced into the environment in a soluble form

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through wet and dry precipitation. Finally, it is either adsorbed on settling particles (scavenged) and deposited in marine or lake sediments, or effectively retained on the surface of continental sediments. Immobilized and isolated from the exchange cycles, this cosmogenic radionuclide then decreases according to its own half-life and thereby becomes a potential tool for dating reservoirs where it has accumulated.

However, the absolute ^{10}Be concentration depends on variations in environmental parameters such as sedimentation rate, mineralogical composition, grain size, and so on. Its use as a dating tool requires overcoming the temporal changes in these parameters by normalizing the ^{10}Be concentration to that of the stable ^9Be isotope, which has a strictly identical chemical behavior.

Present in the minerals constituting terrestrial rocks, stable ^9Be is brought to oceans and lakes from rivers, winds, and hydrothermal fluids after weathering and erosion of these rocks. Although most of it stays in the sedimentary particles, a proportion is dissolved and remains in a soluble form in the acidic medium of watercourses, and finally rapidly adsorbs onto the particles that settle in the more alkaline ocean or lake environments.

Given their different pathways in the terrestrial environment, only the soluble form of both beryllium isotopes can be homogenized before adsorption onto the particles and sediment deposition. Adsorbed on the surface of the particles with a ratio representative of the water mass that contained them, the ^9Be and ^{10}Be isotopes participate in the formation of the authigenic phase (the phase formed from dissolved elements) of the sediments. Only this authigenic phase should be considered for dating.

The authigenic $^{10}\text{Be}/^9\text{Be}$ concentration ratio will therefore have to be determined in the authigenic phase extracted using a specifically developed leaching method. The latter was validated by studies demonstrating that the ratios measured in the authigenic phase leached from sediments at the interface with seawater were equal to those measured in the dissolved phase of the overlying seawaters. The dates are then obtained using the classical equation of radioactive decay: $N_t = N_0 \cdot e^{-\lambda t}$ (where N_t is the

measured authigenic ratio; N_0 the initial authigenic ratio; λ or $\ln 2/T_{1/2}$ the radioactive decay constant; and t the age of the sediment).

Like any radiochronological dating method, the dating method based on measuring the authigenic $^{10}\text{Be}/^9\text{Be}$ ratio from sedimentary deposits is applicable only if the sediments remained as a closed system (free of losses and/or gains with the external environment) since their deposit, and if it is possible to constrain the initial authigenic $^{10}\text{Be}/^9\text{Be}$ ratio (N_0), namely, the value of the initial stock when the losses due to the sole radioactive decay initiate.

This dating method, theoretically applicable for a period of time ranging from 0.2–10 Ma, has been successfully applied to the dating of sedimentary units in the Chad Basin (Lebatard et al. 2010).

In-situ produced cosmogenic nuclides

Application to dating of the in-situ produced cosmogenic nuclides is based on the fact that their production is limited to the first few meters below the Earth's surface. Indeed, the cosmic ray particles rapidly dissipate their energy during their nuclear interactions with the surface rocks because of the density of the latter, which implies that the intensity of the cosmic rays and therefore the in-situ production of cosmogenic nuclides decreases exponentially with the rock depth. The dating method does not therefore rely on the radioactive decay of an initial stock, as previously discussed, but on measuring the concentration of newly produced cosmogenic nuclides having been accumulated in the selected mineral after a geological process has brought it close to the surface. The event dated is therefore the event causing the exposure to cosmic radiation. It must, however, be assumed that the dated substrate was buried deep enough to be protected from the effects of cosmic radiation before being brought to the surface.

Assuming that the gains in in-situ produced cosmogenic nuclides are due solely to cosmic-ray induced nuclear interactions in the sampled material, while the losses result from both

radioactive decay and denudation, the cosmogenic nuclides thus accumulate in the rocks until their concentration reaches a steady state corresponding to a state where production induced by nuclear reactions equals losses by radioactive decay and denudation. The more active are the denudation processes, the more rapidly is this steady state reached (Gosse and Phillips 2001).

Following geomorphological and geological studies demonstrating the blocking of the Chauvet cave paleoentrance by rockfall deposits, the cosmic-ray exposure (CRE) dating method has been applied to the Chauvet cave. The in-situ produced ^{36}Cl concentration measurements performed on surface samples from the three concave rockslide scars located on the 47-m high cliff overhanging the cave paleo-entrance date the first rockfall event back to 29,000 years ago, and the most recent one that permanently blocked the paleoentrance to at least 21,500 years ago. These ^{36}Cl dates confirm the accuracy of the radiocarbon ages (Sadier et al. 2012).

Burial dating

Environmental changes or human activities can induce burial of surface samples previously lying on areas affected by denudation. Then, below a depth limit, the only process operating is radioactive decay of the isotope in question. In this case, for any surface being eroded, the significantly different ^{10}Be and ^{26}Al radioactive decay constants imply that the $^{26}\text{Al}/^{10}\text{Be} = f([^{10}\text{Be}])$ curve evolves between two limit curves defining an area called the “island of the stationary states” (Figure 1). The upper envelope of this surface corresponds to the set of solutions for finite exposure duration at a zero denudation rate, while the lower envelope corresponds to the set of solutions for different denudation rates at infinite exposure duration. These two curves define three zones in the $^{26}\text{Al}/^{10}\text{Be} = f([^{10}\text{Be}])$ diagram. The “forbidden zone” is the area to the right and above the upper envelope curve. Any point in this zone cannot be explained by a geomorphological model and therefore most probably results from an analytical error. The

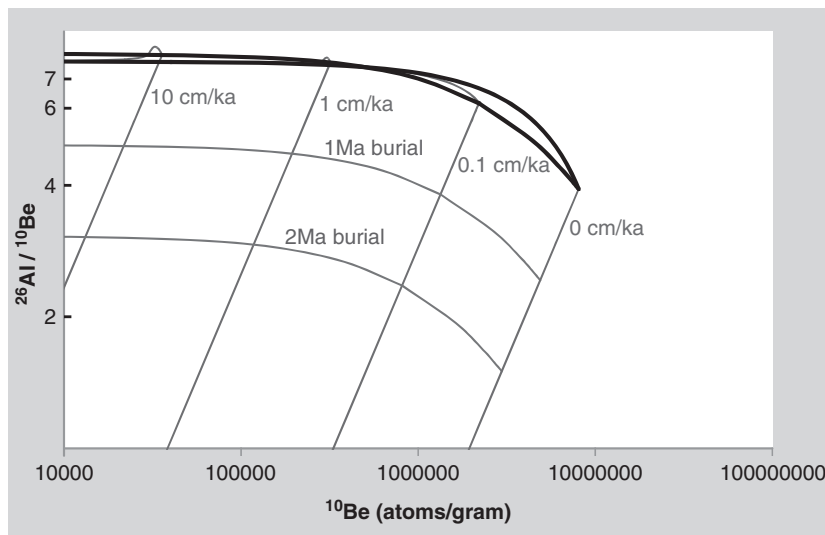


Figure 1 $^{26}\text{Al}/^{10}\text{Be} = f([^{10}\text{Be}])$. The upper curved lines delimit the “island of the stationary states” zone. The parallel curved lines below denote both the ^{10}Be concentrations and the $^{26}\text{Al}/^{10}\text{Be}$ ratios reached after their corresponding burial duration for denudation rates ranging from 0 to a few 10 cm/ka. The straight diagonal lines exhibit the evolution of both the ^{10}Be concentration and the $^{26}\text{Al}/^{10}\text{Be}$ ratio due to radioactive decay for various samples buried from surfaces experiencing the indicated denudation rate.

zone between the two limit curves corresponds to all possible ^{10}Be concentrations and $^{26}\text{Al}/^{10}\text{Be}$ ratios for surfaces undergoing denudation. The zone to the bottom left of the “island of the stationary states” corresponds to all possible ^{10}Be concentrations and $^{26}\text{Al}/^{10}\text{Be}$ ratios for surfaces undergoing or having undergone burial. Indeed, when a previously exposed surface is finally buried enough to be protected from cosmic rays, then losses due to radioactive decay alone imply a decrease in concentrations of the cosmogenic nuclides. These decreases, depending on the half-lives of the considered nuclides, imply for the $^{26}\text{Al}/^{10}\text{Be} = f([^{10}\text{Be}])$ diagram an evolution such that any point initially corresponding to a concentration and a ratio in the “island of the stationary states” evolves down and to the left of this zone. The analysis in the $^{26}\text{Al}/^{10}\text{Be} = f([^{10}\text{Be}])$ diagram of the data obtained from the samples therefore allows the determination of how long they have been buried. The time range that can be investigated using this burial dating method extends from about 0.2 Ma up to 5 Ma.

This burial dating method has most notably been applied to sedimentary layers containing fossils and/or artifacts of paleo-anthropological interest (Partridge et al. 2003; Balco and Rovey 2008; Granger et al. 2015).

SEE ALSO: Cosmogenic Dating; Dating in Archaeology

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Uranium-Series

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Uranium (U) is a chemical element with atomic number 92—that is, the nucleus contains 92 protons—which is part of the actinide group of the periodic table. There are three main naturally occurring U isotopes (^{238}U , ^{235}U , and ^{234}U) (see ISOTOPES), all of which are radioactive. ^{238}U and ^{235}U are starting isotopes (parents) of so-called decay chains, where a series of decay products (daughters) are also radioactive. There are three such decay chains; each starts with an actinide nuclide (the third decay chain starts with ^{232}Th) and ultimately ends with a different stable isotope of lead (Pb). ^{234}U is part of the ^{238}U decay chain, which is partially shown in Figure 1.

U and its daughter nuclides (U-series) are commonly used in geosciences as tracers or as a chronological tool, a good overview of different applications of which can be found in Bourdon et al. (2003). This entry here focuses on U-series dating, in particular $^{230}\text{Th}/\text{U}$ (or U-Th) dating, which is the most important application for archaeological sciences (see DATING IN ARCHAEOLOGY).

Generally, the temporal evolution of the activity ratio between ^{230}Th and U (^{238}U and ^{234}U) provides a timer for the time elapsed since a constrained fractionation. In an undisturbed material, all radioactive daughter nuclides of the decay chain reach a steady state of radioactive equilibrium with the parent nuclide. In other words, in rocks that formed millions of years ago we find the same activity for all daughter nuclides (except the final Pb isotope). However, natural processes such as dissolution or leaching of host rock can disrupt the state of equilibrium between the activity of parent and daughter isotopes, because U is soluble in natural waters, whereas Th is largely insoluble in natural waters. The same principle applies to ^{231}Pa and its parent ^{235}U of the ^{235}U decay chain, because Pa is also insoluble.

As a consequence, ground waters, rivers, and seawater contain dissolved U but essentially no Th (or Pa), and, in contrast to U, Th (or Pa) is not incorporated in secondary carbonates which precipitate from these waters, resulting in an initial $^{230}\text{Th}/\text{U}$ (or $^{231}\text{Pa}/^{235}\text{U}$) disequilibrium.

This applies, for example, to marine carbonates like reef and deep-sea corals or terrestrial carbonates like speleothems (see CAVES AND FISSURES). The initial concentration and hence activity of ^{230}Th in the carbonates, $(^{230}\text{Th})_{\text{init.}}$, is zero, which means that the U-Th “timer” is reset and immediately started again due to the presence of U. In the case where carbonate remains closed thereafter (i.e., both U and Th isotopes are neither lost nor gained), the development of $(^{234}\text{U}/^{238}\text{U})$ and $(^{230}\text{Th}/^{238}\text{U})$ is described by equations (1) and (2) (see Ivanovich and Harmon (1992) for derivation):

$$\left(\frac{^{234}\text{U}}{^{238}\text{U}}\right)(t) = \left(\left(\frac{^{234}\text{U}}{^{238}\text{U}}\right)_{\text{init.}} - 1\right) e^{-\lambda_{234}t} + 1 \quad (1)$$

$$\begin{aligned} \left(\frac{^{230}\text{Th}}{^{238}\text{U}}\right)(t) = & (1 - e^{-\lambda_{230}t}) \\ & + \left(\left(\frac{^{234}\text{U}}{^{238}\text{U}}\right)(t) - 1\right) \\ & \frac{\lambda_{230}}{\lambda_{230} - \lambda_{234}} \left(1 - e^{-(\lambda_{230} - \lambda_{234})t}\right), \end{aligned} \quad (2)$$

where $(^{234}\text{U}/^{238}\text{U})_{\text{init.}}$ is the initial $(^{234}\text{U}/^{238}\text{U})$ activity ratio and λ_i are the decay constants for ^{230}Th and ^{234}U , respectively. However, equations (1) and (2) are only valid if two fundamental conditions are fulfilled: (1) there is no presence of initial ^{230}Th ; and (2) the system remains closed after deposition. If so, the measurement of present-day $(^{234}\text{U}/^{238}\text{U})$ and $(^{230}\text{Th}/^{238}\text{U})$ allows the iterative calculation of the time since the formation of the mineral. Figure 2 shows the temporal development of $(^{230}\text{Th}/^{238}\text{U})$ for the simplest case where $(^{234}\text{U}/^{238}\text{U})_{\text{init.}} = 1$. As a rule of thumb, equilibrium is reached again

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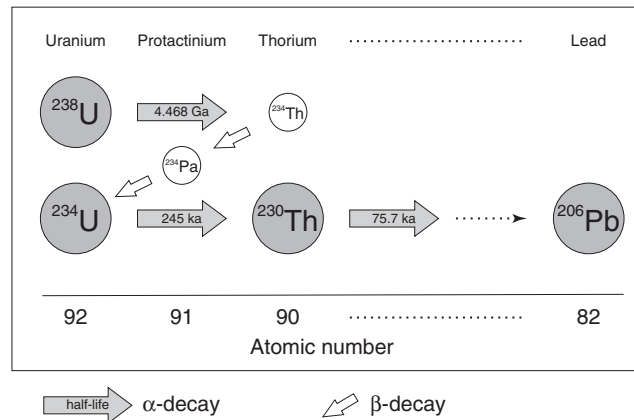


Figure 1 Schematic drawing of the ^{238}U decay chain. Small circles indicate short-lived intermediate decay products. Relevant half-lives of decays are given in the arrows.

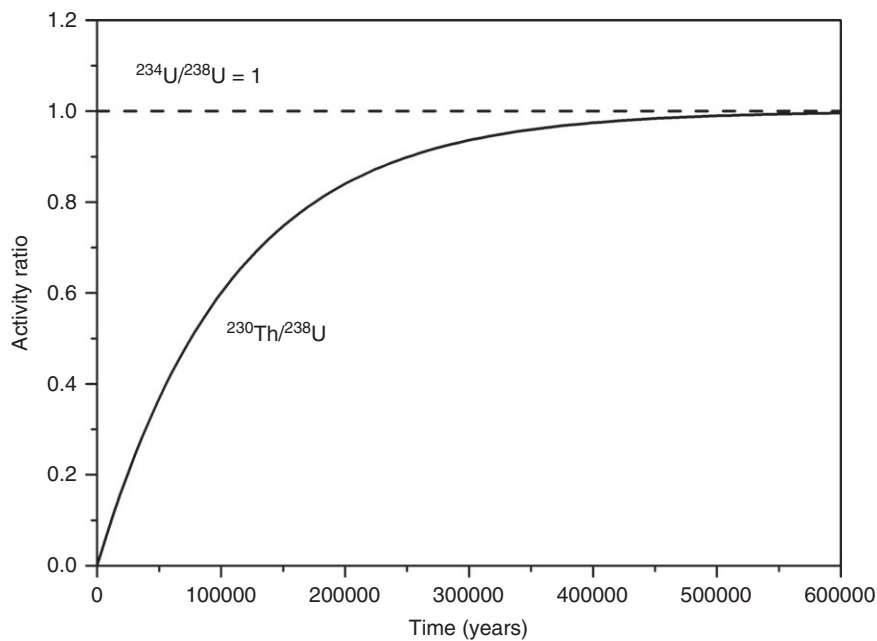


Figure 2 Temporal evolution of the $^{230}\text{Th}/^{238}\text{U}$ activity ratio (for the simplest case with $^{234}\text{U}/^{238}\text{U} = 1$) after Th was removed from the system.

after 500–600 ka (thousand years) which is the limit for this dating technique.

Using the $^{230}\text{Th}/\text{U}$ method it is possible to date the time of precipitation of speleothems like stalagmites, stalactites, flowstones, and CaCO_3 crusts. It can also be applied to open-air spring deposits such as travertine and tufa, although these typically show a relatively high degree of

dirt inclusion, so-called detritus, which usually violates the first fundamental condition of no initial Th. In some cases, $^{230}\text{Th}/\text{U}$ dating is applicable to lacustrine carbonates, or—with caution—to some biogenic materials such as bones, teeth, molluscs, and egg shells, although these are known to be an open system for U and therefore require a suite of analyses at high

spatial resolution (e.g., using laser ablation techniques) to assess potential U mobility. U uptake or loss assumptions are then used for a model age calculation.

Dating of CaCO_3 formation can provide important age constraints for associated archaeology (see ARCHAEOLOGICAL RECORD). Flowstones in caves, for example, are often found in a stratigraphic relationship to archaeological excavations and can be used to constrain the age of underlying (minimum age) or overlying (maximum age) sediments. Speleothems like broken stalagmites and stalactites, specifically so-called straw stalactites, are frequently found inside excavated sediments. These speleothems formed before they were buried in the sediments and thereby can serve as a maximum age constraint for the associated layer. Dating of a post-sedimentation precipitate, which can occasionally be found in sediment voids, provides a minimum age for the surrounding sediment accumulation. In some cases, CaCO_3 precipitated on the surface of archaeological artifacts, for example on skeleton bones. $^{230}\text{Th}/\text{U}$ dating of the CaCO_3 coating on the bone surface provides a minimum age for the archaeological find. The same principle applies for $^{230}\text{Th}/\text{U}$ minimum age constraints for paleolithic cave art derived from CaCO_3 crusts that formed on top of the art. Where cave art is found on a speleothem formation, dating of the underlying CaCO_3 can also provide a maximum age.

Applications of U-series dating in archaeology are not restricted to cave sites. Archaeological finds are also frequently found, for example, in relation to travertine formations. Where a stratigraphy of the travertine and the archaeology can be established, U-series dating can be used as a chronological tool as well. Unfortunately, direct U-series dating of biogenic material like bones and teeth, often found in archaeological sites, is an exception since these materials are usually open systems.

$^{230}\text{Th}/\text{U}$ dating requires precise and accurate measurement of the relevant U and Th isotope abundances to obtain the isotope activity ratios needed to calculate an age according to Equation (2). The isotopes ^{238}U , ^{234}U , and ^{230}Th decay by alpha emission (Figure 1) and have different atomic masses, and thus two methods are commonly used for U and

Th isotope measurements: alpha spectrometry and—more precise—mass spectrometry (MS). Both techniques require prior chemical separation and purification of U and Th from the CaCO_3 matrix. Since U and Th behave differently during chemical separation and purification treatment, a tracer is required, which is a solution with known accurately calibrated concentrations of noncommon U and Th isotopes, for example ^{233}U , ^{236}U , and ^{229}Th . A defined quantity of the tracer needs to be added to the sample prior to the separation procedure (so-called isotope-dilution technique).

Most precise and accurate U-Th isotope ratio measurements can be done with multiple collector (MC) MS (see MASS SPECTROMETRY (MS)) techniques, such as thermal ionization mass spectrometry (TIMS) and inductively coupled plasma mass spectrometry (ICPMS). Generally, state-of-the-art MC-ICPMS techniques require smaller sample sizes and provide the highest precision. For $^{234}\text{U}/^{238}\text{U}$ and $^{230}\text{Th}/^{238}\text{U}$, precision in the range of 1–2 ‰ can typically be achieved and the limit for $^{230}\text{Th}/\text{U}$ -dating is in the range of approximately 600 ka. Precision of the U-Th dating depends on the age of the sample: a sample with an age around 100 ka can be dated with a precision of several per mille (i.e., several hundred years); samples with an age older than 400 ka and U-series activity ratios close to secular equilibrium have dating uncertainties of several percent.

The required CaCO_3 sample sizes for U-Th dating depend on the U concentrations in the material to be analyzed. Most carbonates have U concentrations larger than 10 ng/g, and in most cases 10–100 mg CaCO_3 are sufficient. ^{230}Th concentration in secondary carbonates is variable in time as it is not present when carbonate forms and then starts to build up. Therefore, the sample size needed for precise ^{230}Th measurement depends on U concentration and age of the sample; in most cases, a sample size between 10 and 100 mg is still sufficient.

The reliability of U-Th ages strongly depends on the closed system of the dated material and negligible initial ^{230}Th . Presence of initial (or detrital) Th is tested by determining the concentration of common Th (^{232}Th) in the sample. In the case of significant amounts of ^{232}Th , a correction for initial ^{230}Th needs to be applied.

This is based on a detrital $^{230}\text{Th}/^{232}\text{Th}$ activity ratio—for example, measured on an insoluble detrital fraction. The detrital $^{230}\text{Th}/^{232}\text{Th}$ can also be constrained by a so-called isochron, which is derived from measurements on a set of coeval subsamples. In the absence of such constraints, the detrital correction is done using a so-called bulk earth value of the upper continental crust.

A single U-Th age does not provide any information on whether the dated material represents a closed system or not. The most rigorous reliability test for a U-Th date is to employ the alternative ^{235}U -series and measure $^{231}\text{Pa}/^{235}\text{U}$ in addition to $^{230}\text{Th}/\text{U}$ on the same material. In the case of an open system, the two independent decay chains will be disturbed to different levels, and U-series ages will not yield the same result. With concordant U-Th and U-Pa ages, confidence can be placed in accuracy of the results. However, U-Pa cannot be determined to the same degree of precision as U-Th and small deviations may not be detected. U-Pa analyses also require much larger sample sizes due to a significantly smaller abundance of ^{235}U ($^{235}\text{U}/^{238}\text{U}_{\text{conc}} = 0.0073$) and thus cannot be employed in many cases. Therefore, it is usually recommended to perform repeat $^{230}\text{Th}/\text{U}$ analyses where open systems cannot be excluded. Stalagmites, flowstones, or other carbonates that form with internal stratigraphic constraints provide an additional possibility to check reliability, since ages of subsamples along the growth axis must become progressively younger from bottom to top.

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Varve Chronology

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History of “varve chronology research” and current methodologies applied in varve sequences

Varves are defined as finely laminated sediments that occur in aquatic environments with an annual cycle of deposition. The term “varve” (Swedish: *varv* meaning layer) was originally introduced by the Swedish geologist Gerald De Geer for glacio-lacustrine sediments. He suggested that varves represented annual cycles, with silt layers deposited during the melting season while finer, clayey sediments settled in winter when the lake was ice-covered. De Geer (1912) demonstrated, for the first time, the use of varve counting as a chronological tool in ice retreat history. Since his pioneering work, many other scientists have tried to achieve high-resolution chronologies by counting rhythmic sediment layers. For example, varve researchers in the 1920s used the “varve” concept of De Geer to quantify sedimentation rates in Lake Geneva by counting rhythmic layers that were thought to be annual. Four decades later, the onset of radiometric dating demonstrated that the lamination reflected deposition of irregularly distributed clastic layers that did not respond to annual cycles.

This raises important issues regarding the procedures to assure robust chronologies using laminated sediments. First, in order to develop an adequate varve-based chronology, a preliminary depositional conceptual model describing the structure and annual nature of the sediment cycles is needed. Second, the methodology and error estimation techniques applied to obtain the varve age-depth model should be

carefully selected depending on the varve’s quality, nature, composition, and thickness. Several methodologies have been used and tested in the varve community during recent decades. Thick varves can be counted by detailed visual inspection of cleaned fresh sediment and from high-resolution photographs from cores of open halves. Thinner varves require further microscopic investigations. Unconsolidated sediments are embedded with epoxy resins to obtain polished blocks that allow thin section preparation to perform high-resolution microfacies analyses and varve counting. The recent development of efficient computer-based image analysis has also resulted in a third methodology based on automated or semi-automated varve counting from digitalized varve sequence photographs. Geochemical analysis (mostly based on micro X-ray fluorescence (μ XRF) core scanner techniques) can also provide additional support for varve age determination based on the distinct elemental composition of the different layers. This technique is useful when varve differentiation is not clear by visual and/or microscopic investigations. Quantification of errors in varve chronologies based on replicated varve counts on multiple cores, ideally carried out by independent experienced researchers, is also a requisite to achieve reliable age-depth models. Finally, a validation of the varve age-depth determination should be achieved by comparison with other independent dating methods (e.g., ^{14}C , ^{210}Pb , and ^{137}Cs radiometric dating, palynological stratigraphies, tephrochronology, paleomagnetism) that would reveal the accuracy of the varve chronology. If extended to the present day including recent surface sediment, varve chronologies can be regarded as absolute, that is, representing a calendar-year timescale. On the other hand, if the varve sequence has intervals without preservation of annual cycles due to changes in the depositional and limnological dynamics, the varve chronology is defined as floating. In these cases, researchers use marker-horizons related to well-known historical or environmental events to anchor the chronology.

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Varve types

The formation and composition of varves is governed by a suite of climatological, hydrological, limnological, and biological processes. Although there is not a unique environment leading to the formation of varves, they mostly occur under anoxic bottom conditions that impede bioturbation and burrowing activities that may disturb the laminations. Varves are composed of sets of laminae deposited during different seasons within the annual cycle, and, consequently, strong environmental seasonality is also required to create these laminated deposits. Three main types of varves are reported in the literature:

- Clastic varves, such as the glacio-lacustrine varves originally described by De Geer (1912). They respond to physical processes (e.g., freeze–thaw annual cycles) and are mostly composed of mineral detrital particles of different grain sizes.
- Biogenic varves, whose formation is mostly governed by biological processes. Among the different biogenic varves, calcareous varves are the most common, characterized by seasonal bio-induced precipitation of calcium carbonate related to algal blooms.
- Evaporitic varves, controlled by variable physico-chemical processes that modulate the seasonal precipitation of carbonate and sulfate mineral phases. These varves are less common and occur in arid and semi-arid regions.

Spatial distribution of varve sequences

Varve sequences occur in a wide range of depositional environments (mostly in marine, estuarine, and lacustrine settings). A recent review of geographic settings and varve chronologies shows an irregular worldwide distribution (Ojala et al. 2012). A total of 99 lacustrine varve sedimentary sequences with reasonably robust varve chronologies were reported. These researchers excluded varve chronologies with temporal extension of less than 100 years, since many modern varve settings show varve precipitation as a result of modern anthropogenic eutrophication during the

last decades. A global compilation of Quaternary marine varved sedimentary records reported 52 sites (Schimmelmänn et al. 2016). These global varve-based chronologies highlighted the heterogeneous spatial distribution of varve settings. Marine varves have been mostly described in the northern hemisphere. Similarly, lacustrine varve chronologies are more widespread in Europe and North America. Marine varves have mostly been documented close to the continent, although they also occur in deep-sea environments and display different temporal intervals. On the other hand, varves preservation is favored in lacustrine basins with meromictic conditions—that is, permanent anoxic hypolimnion—sheltered from the wind. Maar lakes, deep tectonic basins, and karstic lakes provide examples of potentially good sites for varve formation and preservation.

Quaternary varve chronologies: the example of Lake Suigetsu

Most of the lacustrine varve chronologies are constrained to the Late Holocene. Only a few records extend to periods before the onset of the Holocene, such as the Central European lakes Holzmaar and Meerfelder Maar. However, the longest lacustrine varve chronology to date comes from Lake Suigetsu in central Japan. The sediments in this tectonic lake include biogenic and clastic varves deposited over the last 70,000 years. This varved sequence has been studied by numerous researchers since the early 1990s due to its high potential to provide a terrestrial radiocarbon calibration model. The development of a robust varve chronology in this lake would eventually result in a high-resolution chronology of paleoclimatic changes that could be compared to other key climate records worldwide. After two decades of detailed sedimentological and geochemical analyses carried out by researchers from different institutions, the varve chronology has served to calibrate and complete a terrestrial radiocarbon chronology beyond the tree ring limit for the period 11.2–52.8 kya (Ramsey et al. 2012). The achievement of a calibration of the terrestrial radiocarbon curve for the last 50,000 years has obvious implications not only for paleoclimate

research but also for paleoanthropological and geoarchaeological studies.

Varves as a paleoenvironmental proxy for archaeological studies

Since the time of De Geer, but especially since the end of the 1990s, varve researchers have tried to link environmental conditions reconstructed from varve sequences to human societal evolution. The high-resolution climate and environmental information contained in these records has been used by paleoclimatologists and archaeologists to evaluate their effect on the rise and demise of humankind during the last millennia. One of the best-known examples is the anoxic Cariaco Basin in the southern Caribbean Sea, which preserves clastic and biogenic varves deposited during the last 1,500 years. The seasonally resolved chronology coupled with geochemical measurements based on the titanium content in the sediment as a proxy for riverine input has allowed the reconstruction of regional rainfall changes (Haug et al. 2003). These authors suggested that centennial-scale decline in rainfall led to a large regional drought, which played a decisive role in the collapse of Classic Maya civilization in the Terminal Classic Period. This varve sequence also provided a more refined temporal framework to compare archaeological-based chronologies.

Several lacustrine varve sites in the eastern and western Mediterranean have also shed light on the environmental forcings that influenced past human migrations. Lake Zoñar, a small karstic lake located in a semi-arid region in southern Iberia, provides a floating varve chronology composed of biogenic varves for the Iberian–Roman Humid Period (1600–2600 BP; Martín-Puertas et al. 2009). The paleohydrological proxies derived from this sequence revealed more humid conditions in southern Spain coinciding with the flourishing of the Iberian culture and the Roman Conquest. Lake Montcortès, another karstic lake located in northern Iberia (southern central Pyrenees), contains an absolute varve chronology spanning the last 2,800 years (Corella et al. 2016). Detrital layers embedded in the biogenic varve succession provided a seasonally-resolved rainfall

record from the western Mediterranean. An exceptional, centennial-long period with very low rainfall frequencies between 370 and 670 CE was synchronous to the collapse of agricultural-based societies at the end of the Roman Empire and the onset of Visigoth invasions. Several geochemical and biological indicators in these Iberian sequences point to relatively warmer and more arid conditions during Early Medieval times (somehow synchronous to the Medieval Climate Anomaly) compared to the post-fourteenth century (Little Ice Age). Varve chronologies are also available from eastern Mediterranean sites. Interestingly, the opposite hydrological signal was reconstructed from Lake Nar Gölü, a maar lake located in Cappadocia, central Turkey, with more humid conditions prior to 1500 CE. The Nar Gölü varve chronology spans the last 1,720 years. Dean et al. (2013) reconstructed the precipitation seasonality in the region using stable isotopes ($\delta^{18}\text{O}$) in diatoms and carbonates. Harsh winters with increased snowfalls combined with dry summers resulting in a negative water balance were frequent between 301 and 561 CE. This marked seasonality may have led to a decline in agricultural-based societies in the Near-East. This see-saw pattern from the Mediterranean exemplifies the use of varve chronologies to determine the synchronicity of environmental changes and the consequences of human societies' evolution and migration patterns.

Unfortunately, varves are not always located in areas of great significance for anthropological and archaeological studies. The geoarchaeological community would greatly benefit if new “varved” sedimentary sequences are found in Africa and the southern hemisphere in order to increase the spatial resolution of these annually-resolved paleoenvironmental archives. An example is the 25-ka sedimentary sequence from crater Lake Challa (Kenya/Tanzania) located on the eastern slopes of Mount Kilimanjaro and with an absolute varve chronology for the last 3,000 years and a floating varve chronology during the Last Glacial Period (Wolff et al. 2011). As the thicknesses of the biogenic varves were directly related to rainfall dynamics, interannual to centennial-scale changes in ENSO-related rainfall patterns that had controlled flooding and drought variability in the region could be reconstructed. These environmental changes had drastic impacts on

past human habitation and food security in eastern Africa. New varve-based chronologies and paleoenvironmental, paleoanthropological, and archaeological research in this region will shed light on past environmental–human interactions in the cradle of humankind.

Future research coupling varve and archaeological studies will play a key role in the human–climate–environmental debate, including the influence of water availability on past human migrations and evolution, and/or the influence of catastrophic events (such as major earthquakes, storms, droughts) on human societies during the last millennia.

SEE ALSO: Climate Change and Dating; Dating in Archaeology; Lake Deposits

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Air Pollution

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Air pollution is the perturbation of atmospheric conditions, through inputs of materials and energy, overwhelmingly owing to human activity. Air pollution parallels the evolution of human industrial activity: the extraction and conversion of global resources for capital gain, with indifference (until comparatively recently) to the fate of the waste expelled into the atmosphere. Global industrialization, fossil fuel combustion, and technological innovation have changed the natural variations in atmospheric conditions and composition to the present interlinked human-atmospheric global system (Steffen, Crutzen, and McNeill 2007). Air pollution has become a society-driven, planetary process capable of being detected across interstellar space (Stevens, Forgan, and O'Malley James 2016).

Air pollution requires a source and mechanism of atmospheric dispersal, followed by a process of contamination concentration that has a distinguishable effect on human and natural systems. Simple source, sink, and effect concepts are complicated by chemical reactions in the atmosphere that convert primary pollutants into secondary pollutants. Primary pollutants are directly emitted from sources, including sulfur dioxide (SO_2), nitrogen dioxides (NO , NO_2 commonly referred to as NO_x), volatile organic compounds (VOC) such as hydrocarbons, including methane (CH_4), carbon monoxide (CO), and metal compounds. Secondary pollutants are a range of gases, particulates, and aerosol mixtures created by the interaction between primary pollutants and atmospheric processes, for example the photodissociation of industrial emissions of chlorofluorocarbons into ozone (O_3)-depleting substances and a chain of reactive intermediates between mixtures of both primary and secondary pollutants.

Contrasting effects also occur with some atmospheric pollutants. For example, the sulfate aerosols from fossil fuels contribute to acid rain but also cause atmospheric cooling by reflecting solar radiation back into space. Local and regional temperature change due to human activity (vegetation patterns, urban development) should also be considered as air pollution, not least because of its co-effect with other pollutants on mortality rates due to high temperatures (Willers et al. 2016).

Early human activity largely replicated sources of natural atmospheric contamination through burning for hunting, fuel use, and land clearance for agriculture (see ENVIRONMENTAL MANAGEMENT WITH FIRE). Emissions of gas and dust from volcanic activity (see ARCHAEOLOGICAL VOLCANOLOGY) during the Holocene had effects, from local to global (tropospheric cooling, shading, acid deposition), that were not observed until the Industrial Revolution. Poor domestic air quality and increased mortality caused by inadequate ventilation, low-grade fuels, and inefficient fuel combustion would have been common in early fire use and remain global problems (WHO 2014). The physical unpleasantness of sitting in a smoke-filled interior (balanced nonetheless with the benefits: warmth, reduction of biting insects) would have been a driving factor in technological advances such as the development of the chimney. Early industrial methods of ore extraction and refinement led to both more advanced furnace techniques and emission products being deposited locally and globally, with direct and indirect impacts on human and ecological communities. Evidence for early industrial air pollution alone having an effect on human mortality rates is restricted, owing to (a) other factors detrimental to human health (domestic air quality, disease, subsistence); (b) the range of other pathways (ingestion of contaminated water, foodstuffs grown on waste contaminated soil) that also determined biogeochemical intake; and (c) taphonomic factors (see TAPHONOMY).

Classical Greek and Roman, then Arabic, Chinese, and early European writers noted and

discussed the degradation of health due to the poor air quality that accompanied the growth of towns and cities and the concentrated use of biomass fuels (wood, crop residues, dung, and coal). Air pollution, however, radically changed with the unprecedented social and economic changes of the Industrial Revolution and the widespread use of coal for industrial and domestic fuel. Atmospheric concentrations of sulfur, soot, smoke, and other industrial emissions increased in towns and cities, along with a population that came to work with steam-powered engines and other technological developments from manufacturing. Definitive skeletal or pathological evidence of increased mortality, during this period, from air pollution alone is, however, scarce, even where there are contextual and historical indications of occupational and diffuse exposure to poor air quality (DiGangi and Sirianni 2016; Roberts et al. 2016).

The combination between an increased population density and the understanding of disease vectors and obvious signs of poor air quality (visible smoke, soot, corrosive damage to buildings) prompted early attempts at statutory air-quality legislation that clashed with economic progress. Throughout the nineteenth and early twentieth century, in cities and towns in the United Kingdom and other rapidly urbanizing countries, the demands for production and wealth generation were greater than any response to air pollution and its impact on ecosystems and human health. Although some correction occurred through improved working conditions, combustion technology, and the dilution of emissions due to urban expansion, air quality continued to deteriorate. Severe smoky fogs (smogs) in densely populated areas coincided with the high mortality rates that finally gave momentum to legislature such as the Clean Air Acts (UK, 1956, 1968) and Air Pollution Control Acts (USA, 1955, 1963). These, along with technological and social changes, reduced much of the local- and regional-scale negative effects of air pollution by the mid-twentieth century. Due to the colossal twentieth-century population growth and planetary demand for energy, which could be sustained only by fossil fuels, air pollution in the mid- to late twentieth century became widely recognized as a global phenomenon. Air pollution issues such as the acidification of rain and surface waters through

SO₂ and NO_x, the depletion of polar stratospheric ozone as a result of chlorofluorocarbons, and the deposition of fossil fuel-associated toxic metals into ecosystems were identified with the help of scientific advancements in atmospheric chemistry, environmental monitoring and modeling, and paleoenvironmental research. More rapidly and effectively than in the mid-nineteenth to early twentieth century, a scientific understanding of the processes involved the ability to implement technological solutions (e.g., flue gas desulfurization at power plants); and international political agreements allowed these issues to be “solved,” significant recovery having been achieved in many affected ecosystems. During the same period and up to the present, fossil fuel combustion, automobile emissions, and agriculture have greatly increased the atmospheric concentrations of carbon dioxide (CO₂), methane, and other greenhouse gases.

The challenge of measuring air pollution levels in the past is that of distinguishing and quantifying the material evidence for time-specific atmospheric contaminant loads. Information on past atmospheric contaminants released through human activity over millennia can be obtained from ice core, marine, and high-altitude lake sediment and peat sequences. Types of fuel combusted, gases released, and materials processed are identifiable by means of compositional (e.g., pyrogenic carbon: Thevenon et al. 2010) and isotopic (e.g., ^{206/207}Pb, $\delta^{13}\text{CH}_4$, $\delta^{15}\text{N}$) measurements. With good chronological control both in the depositional archive and in contexts from areas of industrial release, variations in the magnitude and composition of the contaminants released can be matched (Rosman et al. 1997) and an estimate of past air pollution levels be made.

Records of atmospherically transported trace contaminants in remote environmental archives provide a clear signal of increased atmospheric contaminants, but evidence of local air pollution requires more detailed, site-scale investigation. Evidence from early metal-working centers—in the form of skeletal metal levels, volumes of furnace waste, contaminated soils, and sediments contemporaneous with the operation and paleoecological evidence of vegetation changes—indicates that air pollution would have been prevalent and considerable (e.g., Grattan et al. 2016). At early industrial sites,

however, quantifying past concentrations and trends of atmospheric contaminants is limited by the lack of depositional contexts that preserve time-constrained atmospheric loadings. Taphonomic processes are also critical factors affecting the fossil composition of particles and of products derived from atmospheric deposition. The nature of fuel-combustion products (ash, charcoal) in urban and industrial cultural layers is determined by the distance of the sampling site from the source and by the nature of combustion (fuel type and intensity). There are multiple pathways by which atmospherically transported materials can accumulate in archaeological contexts and in environmental systems that are asynchronous when it comes to the timing of contaminant inputs, including catchment erosion/remobilization and postburial diagenesis.

Evidence of preindustrial atmospheric conditions also comes from preserved crusts on stone monuments and architecture. Like modern crusts on stonework containing high-temperature fossil fuel combustion products, preindustrial crusts contain evidence of lower-temperature wood and charcoal combustion products (Del Monte et al. 2001). Such archaeometric methods are dependent on known exposure periods and on similar taphonomic considerations that apply to detecting combustion products in cultural deposits.

Comparison between proposed atmospherically derived contaminants in archaeological layers and synchronous off-site environmental archives is recommended. Methods developed to assess recent historical atmospheric pollution loads (e.g., spheroidal carbonaceous particles [SCPs], polyaromatic hydrocarbons, trace metals, Pb and N isotopes in lake sediments) can be applied to long-time scales but some, SCPs in particular, are only a consequence of high-temperature fossil fuel combustion unseen until the Industrial Revolution (Rose 2015).

Although dwarfed by the global effects of anthropogenic climate change, air pollution remains a huge and growing health issue, 7 million deaths being annually attributed to it (WHO 2014). Domestic, occupational, and outdoor pollution levels far exceed international health guidelines for NO₂, PM₁₀, and PM_{2.5} (particle matter <10 and 2.5 microns) in many developing nations, especially in African, Indian, and

Chinese cities, given the expanding numbers of both people and vehicles. In developed nations, gases (O₃, NO_x) and particulates from industrial and vehicle emissions remain at chronic levels in many cities, causing ill-health and raised mortality rates (Samoli et al. 2016).

SEE ALSO: Paleoenvironmental Reconstruction; Scientific Revolutions; Water Pollution

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Archaeoentomology

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Archaeoentomology, or the study of insect (and other arthropod) remains in the Pleistocene and archaeological record, contributes to three distinct areas of research:

- Climate, vegetation, and landscape reconstruction (see CLIMATE CHANGE AND DATING and VEGETATION MODELING USING POLLEN DATA)
- Establishing the impact and role of humans in landscape change (see ENVIRONMENT AND LANDSCAPE and INHABITED LANDSCAPES)
- The interpretation of the environment in settlements, the urban landscape, and associated archaeological deposits (see URBAN ENVIRONMENTS).

These studies investigate issues such as deposit formation, human health and hygiene, quality of food supply, the spread of storage pests and synanthropic species, and patterns of past human behavior.

Given the sheer diversity of arthropods (phylum Arthropoda) found in the modern world, the actual number of orders and classes studied archaeologically is surprisingly small, mainly consisting of a narrow range of insects and arachnids. This is due to the extent to which they are preserved in the archaeological record, their relative “interpretive yield,” and the ease of identification of a specific order. The major groups that are routinely studied are beetles (Coleoptera), true flies (Diptera), caddis flies (Tricoptera), true bugs (Heteroptera), bees, wasps, and ants (Hymenoptera), lice (Malophaga), fleas (Siphonaptera), mites (Acari), and nonbiting midges (Chironomidae).

Insect remains can be preserved in the archaeological record in a number of complex ways, meaning that insect death assemblages suffer

from a range of preservation, taphonomic, and selective biases (see FORMATION PROCESSES and TAPHONOMY). There have been various attempts to counter, or at least identify, these problems (Kenward 1978; Smith and Kenward 2012).

Normally, the exoskeletons of insects will disarticulate in the archaeological record into sclerites, but instances of semi-intact or even whole insects are not uncommon. The commonest form of preservation encountered is by anoxic waterlogging, which requires continued saturation of the deposit between deposition and sampling. Suitable deposits are therefore often limited to the “organic crescents” of the northern and southern latitudes where climate and ground water conditions allow waterlogged deposits to develop (Kenward and Hall 2008). Insect remains can be routinely recovered from a range of natural or naturally infilling deposits such as organic sedimentary layers, water channel, valley, and river fills (encompassing a range of reed, wood, and organic fluvial sediments), and peats (see PEAT DEPOSITS). In terms of settlement archaeology, the extent of waterlogged deposits often depends upon the nature of the past and contemporary water tables and how the settlement has developed over time. Equally, the digging of deep features such as ditches, wells, and cess pits to below, or close to, the water table can allow material to become waterlogged, even if the contemporary ground surface remains dry. Deeply stratified urban sites are also thought to become progressively waterlogged as water rises by “wicking” through the deep accumulations of organic material that build up. This can be the case even if the archaeology lies well above the geological water table (Kenward and Hall 2008).

Insects can be preserved through desiccation and freezing, where these conditions persist over time. Instances of insect remains being preserved through the deposition of organic salts (e.g., in packrat middens), carbonization, or by being sealed into deposits in such a way that oxygen is excluded do occur, but remain unusual modes of preservation. At some sites, insect remains also can be preserved by mineral replacement (see FORMATION PROCESSES).

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Recovery, identification, and quantification

The main consideration in terms of sampling for insect remains is to obtain a representative set of material that is relevant to the research questions being posed (see *SAMPLING IN ENVIRONMENTAL STUDIES*). The analysis of Coleoptera and Diptera normally requires a 10-L sample of material if it is to be representative of the population being sampled. Samples are usually taken as continuous slices from an open section in order to assess how the insect assemblages change over time. Well-defined settlement or “natural” deposits are commonly sampled by taking material from each “layer” or context. At many sites, insect remains are recovered from “general biological samples” which are used to also recover plant macrofossils, pollen, and other biological remains (Kenward, Hall, and Jones 1980, 4). If it is not possible to gain access to an open face of a section for sampling, material can be obtained from multiple parallel cores using a Russian auger, though depth control can be problematic (see *CORING*).

Insect remains are normally extracted from sampled sediment using paraffin (kerosene) flotation. After the sediment has been disaggregated, paraffin is added to the material. The paraffin adheres to the chitinous sclerites and when cold water is added the insect remains should float to the surface. The material is then poured onto a 300- μ m-mesh sieve. This process, first established by Peter Osborne (University of Birmingham), is described fully by Kenward and colleagues (1980). Paraffin flotation has been found to be a reliable and efficient method for the extraction of insect remains from waterlogged material, often reaching levels of 80 percent recovery in experimental studies (Rousseau 2011). Other methods of extraction have been proposed, but these have been found to be less efficient (Rousseau 2011). Chironomids and mites have their own extraction methodology. Once a flot has been obtained, the paraffin adhering to the insect remains is removed by washing in detergent and the flot sorted to recover insect remains by hand under a low-power 10X–50X microscope. The resultant insect fragments are then sorted into “morphological groups” by the specialist.

The extraction of insect fragments preserved by other means requires a different approach. Desiccated, charred, and mineral-replaced remains that are greater than 300 microns in size will often need to be hand-sorted from flots or residues resulting from sieving the sample. It is often more efficient to have the paleobotanist pick out these insect remains as well as any plant remains present. At present, the identification of insect remains is mainly based on comparison of the archaeological specimen's gross morphology to modern reference material (see *USE OF BIOLOGICAL COLLECTIONS*), supplemented by the use of modern taxonomic guides, photos, and web-based illustrations. Features that can be useful for determination are general shape, surface microsculpture, and where the pore punctures (which in life hold the insect's sensory “hairs”) are located. Rarely, it may also be possible to identify insects from their genital armature.

Initial quantification of disarticulated insect remains usually occurs by conducting a minimum number of individuals (MNI) count. Fragmented remains of Coleoptera are usually quantified on the head, thorax (pronotum), and left or right elytron (wing case) elements. The minimum number of individuals for Coleoptera counted in this way, therefore, will be the highest score of one of these four elements (i.e., with 1 head, 2 thorax, 3 right elytron, and 2 left elytron; MNI = 3). Whole, or semicomplete, insects encountered (e.g., fly puparia and mites) are usually counted by identifying one specific “identification zone” (usually the posterior or anterior end).

The relative number of insect taxa within assemblages also can be recorded using a range of estimated counts (e.g., an abundance scale) rather than a full enumeration (see Kenward et al. 1985). This is especially useful during the assessment of the research potential of material, or on very large-scale urban sites where many of the insect assemblages recovered from different contexts can be essentially highly similar. Though not statistically proven, it seems very little information is lost by using such estimated counts. It also has become quite common practice to semiquantify archaeoentomological material from urban deposits, where the material is “scanned” for a set period of time (normally 10–15 minutes) to establish its range and diversity.

Analysis

The basic and underlying assumption of insect analysis is that a species' modern ecology will essentially be the same in the past as it is today, thus allowing a straightforward paleoenvironmental reconstruction to occur (e.g., Coope 1977). It has been established that for at least the last one million years, there has been little morphological or physiological evolution of insects in the northern hemisphere, although the distribution of different species has varied greatly (Coope 1977). The first level of insect analysis, therefore, is to obtain known modern ecological information about a taxon, such as temperature range tolerated, ecological behavior, and food preference. This allows specific species identified in an archaeological assemblage to be used as "indicator species" for particular environments, materials, and/or human behaviors (e.g., the "granary weevil" *Sitophilus granarius* is treated as a direct indicator for the presence of grain).

This assumption underpinned Russell Coope's initial attempts at climatic reconstruction using the modern temperature "envelopes" of a number of key species from Pleistocene deposits (Coope 1977). This process subsequently has been refined and elaborated by the use of the "mutual climatic range" model (Atkinson, Briffa, and Coope 1987).

In terms of landscape and environmental reconstruction, initial attempts to use the proportions of indicator species to provide reconstructions of environments, landscapes, and archaeological sites (the so-called mosaic approach) proved problematic. Mainly this is due to a number of biases inherent in the nature of both the formation of insect assemblages and the archaeological record itself (Kenward 1978).

Subsequently, there have been attempts to investigate the nature of insect faunas using combined ecological groupings and a range of multivariate statistics to identify and counter these effects (e.g., Carrott and Kenward 2001; Smith and Kenward 2012) (see also CORRESPONDENCE ANALYSIS and STATISTICS IN ARCHAEOLOGY). In terms of settlement archaeology, recent developments have established that the combining of insect "indicator groups" into larger interpretative "indicator packages" is a useful interpretative tool for a range of biological and archaeological

phenomena (e.g., Kenward and Hall 1997). This has proven to be a successful approach to archaeological interpretation, allowing materials such as stable waste, roofing thatch, craft materials, and sewage (all deposits that share materials such as cereal straw, but with the straw used in different ways) to be identified with some confidence.

Future research and prospects

There is a clear need to increase the range of insects that are routinely studied. Several orders of insects and other classes of arthropods have great potential to function as environmental proxies or archaeological indicators, but they remain underutilized or underinvestigated (for example, the limited use of true flies, caddis flies, and mites).

The study of insect remains is mainly constrained for historical reasons to northern Europe, where the discipline first developed, with limited forays into North America, the Mediterranean, and Eurasia. There is clearly enormous potential for this discipline to develop worldwide.

There continues to be a shortage of trained practitioners in terms of both research and archaeological consultancy work, which constitutes a real threat to the discipline's future. Many of the assumptions and analytical techniques used in the discipline require thorough testing through calibration work, where modern insect faunas collected from a range of materials, landscapes, and deposit types can be compared to the faunas seen in the archaeological record. Additionally, biomolecular techniques are worth exploring, including stable isotopes (see ISOTOPES) and aDNA analysis (see SEQUENCING DNA and DNA: NEXT GENERATION SEQUENCING), in order to investigate the origins and distribution of insect species over time.

SEE ALSO: Paleodemography and Hazards Analysis

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Archaeological Volcanology

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The definition of *archaeological volcanology* can be simply stated as *the science of human adaptation to disasters arising from volcanic eruptions*. As its name implies, archaeological volcanology combines archaeology, a subfield of anthropology or history, and volcanology, a subfield of geosciences. The combination is necessary to understand how humans respond and adapt to volcanic eruptions, and data from all eruptions, from the past to the present, are used in this endeavor. As ethnographic, archaeological, and volcanological data attest, volcanic eruptions can act upon cultural groups as catalysts, as processes, and, rarely, as termination factors (Bawden and Reyecraft 2000; Cooper and Sheets 2012; Gaillard and Dibben 2008; Grattan and Torrence 2007; Ort et al. 2008; Riede 2015; Sheets and Grayson 1979; Sigurdsson 2015). Archaeological volcanology is related to the anthropology and sociology of disaster, as well as to hazards research and management. Volcanic eruptions are just one type of “hazard” that, when combined with an affected human population, can rapidly become a “disaster” that must be dealt with for both individual and group survival.

Volcanic eruptions are some of the most powerful natural phenomena, with their impact on the cultural and natural environment extending far beyond the zone of physical destruction. An eruption is a full sensory experience—these features are seen, heard, felt, and smelled. Eruptions shake the ground; create and sometimes destroy mountains; turn day into night; emit foul-smelling sulfur and other noxious gases; and make roaring, hissing, and knocking sounds that can be heard for hundreds of kilometers.

They are also highly symbolic, emitting red-hot glowing lava from deep within the Earth. As it cools, the lava transforms from a molten liquid to solid rock, which, along with the deposition of tephra (broken pieces of magma thrown into the air), can dramatically alter the landscape, cover long-established territorial markers, and alter or even destroy once-reliable water sources. Prior to the Industrial Age, the world was a quiet place, with a short clap of thunder being the loudest sound regularly heard, and the prolonged roar of an eruption would have been highly alarming and potentially terrifying. Unlike many other natural hazards, volcanic eruptions have an extended duration and can also evolve over time, making human adaptation not only an ongoing process, but one that must be flexible.

As a result of these impacts, volcanoes are well known as destructive to humans, animals, plant life, and property, which may account for the deep-seated fear and awe that characterizes the human–volcano relationship. Eruptions are common in traditional (or oral) histories, generally involving fires and molten rock from deep within the Earth, a place, for many societies, where both gods and people originated. It is not surprising, then, that eruptions are almost always seen as malevolent and often a form of divine punishment or retribution. What is less well known is that eruptions can also have very beneficial effects. Volcanic rock is a prime source for construction material. A thin tephra cover can also serve as a water-retaining, temperature-regulating mulch, allowing areas previously too dry to farm to become productive; bumper crop yields are often reported in areas with less than 15–20 cm of tephra in the years immediately following an eruption. Perhaps most significantly, areas once uninhabitable due to thick tephra cover may gradually transform into fertile agricultural fields. Volcanic soils today support a large proportion of Earth’s population.

One of the difficulties in dealing with a volcanic eruption, both as a disaster and as a research area, is that eruptions have both direct (short-term) and indirect (long-term) effects.

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These can combine (and recombine) in complex ways, and the addition of human cultural variables adds to the difficulty in deciphering these relationships. Direct effects can include death and injury, the destruction of villages and agricultural fields, forest fires, lahars (debris flows), earthquakes, and tsunamis. Indirect effects can include acid fog and rains, cooler temperatures, air pollution-related respiratory issues (see AIR POLLUTION), famine, vegetation destruction (and reduced rate of regeneration), loss of animal habitat, and the removal of large portions of previously productive landscape from human use. Because volcanoes are found across the world and have global effects, they also have the potential to impact different types of societies with varying degrees of social complexity, hierarchy, leadership, religious practices, subsistence systems, community organization, and kinship systems, and who live in a wide range of environmental settings. Even with this extreme variation, recent archaeological volcanology research has suggested that patterned similarities in both the nature of the volcanic eruption and the resulting human adaptation can provide insight into these processes. This research makes clear that to survive and successfully adapt to a volcanic eruption, affected populations need to employ cultural mechanisms that allow for both multiple short-term responses and long-term strategies.

Volcanoes

Volcanoes are the places where magma reaches the surface of the Earth. Volcanologists have classified volcanoes into several different types: scoria (or cinder) cones, maars, shield volcanoes, and stratovolcanoes. However, each eruption, no matter the type of volcano, is unique, and the resulting human response is dependent on the mix of a large, and often unpredictable, set of cultural and natural factors. Large stratovolcano eruptions are the type most familiar to the public. However, the smaller scoria cones and maars are the most common volcanic landform on Earth and the type most likely to impact human groups.

The types of eruption and volcanic landforms associated with them strongly affect the hazards presented by volcanic events and the adaptive processes that affected populations need to employ.

Magma vary greatly in their characteristics. Two very important parameters, magma viscosity and water content, can vary by at least ten orders of magnitude and from around 0 to 8 percent by weight, respectively. These dramatically affect how eruptions proceed—higher water and gas content causes the magma to vesiculate and increase in volume, which in turn increases its surface ascent rate but also causes it to break apart into pieces (pyroclasts). Higher viscosity leads to more explosive breaking of the magma if it is gas rich, and to steeper and less stable volcanic edifices if it erupts as a gas-poor lava.

Low-viscosity magmas (e.g., basalt) allow dissolved gases to escape quickly. Thus, they can produce lava that pours rapidly from the vent or fountain a few to tens of meters into the air before falling and forming lava flows. With somewhat higher viscosities and gas contents, similar magmas can shoot hundreds of meters into the air and produce large (to around 400 m high) piles of pyroclasts around the vent, forming a scoria cone. Less commonly, these eruptions produce columns that rise 5–15 km into the air, similar to many stratovolcanic eruptions. In some cases, basaltic magma interacts with groundwater, flashing that to vapor and exploding to form nuclear-bomb-like craters called maars. These explosions can dramatically affect areas a few kilometers from the vent. Basaltic eruptions tend to be less explosive than other types of eruptions, but the landforms they create (lava flows, broad low-angle shield volcanoes, and scoria cones) are amenable to human occupation, so people often live very close to the eruption sites and may learn to interact with the volcano. Scoria-cone and maar volcanoes usually only erupt once from the same vent for a week to a few years. Large volcanic fields, however, such as the Michoacán–Guanajuato Volcanic Field in central Mexico, can contain hundreds of scoria cones, making entire regions volcanically active and potentially hazardous.

Stratovolcanoes, such as Vesuvius, Fuji, and Mt. St. Helens, are perhaps the most iconic volcano landform. The andesitic to dacitic magma is typically more viscous and gas rich than basalts, leading to more explosive eruptions and thicker lava flows that pile up to form steeper edifices. These volcanoes can produce large pyroclastic eruption columns containing broken chunks of

vesiculated magma that can rise to a height of 30 km and deposit tephra over tens of thousands of kilometers. In large eruptions, the pyroclasts can cross into the stratosphere and spread around the world, in some cases altering climate. The eruption of Tambora in Indonesia is thought to be the cause of the 1816 “year without a summer.” The sulfur aerosols that Tambora emitted were dispersed throughout the northern stratosphere, causing decreased temperatures in North America and Europe that resulted in crop failure, starvation, and the deaths of thousands of people from extreme cold. Pyroclastic flows are also common in stratovolcanic eruptions, consisting of hot gases mixed with tephra that reach speeds of hundreds of kilometers per hour, destroying everything in their path. In addition, the eruptions can spread pumice and ash over the volcano’s slopes that can then be re-mobilized by precipitation, producing destructive debris flows in the valleys around the volcano. Some of these debris flows are hot, a characteristic described in many traditional histories. Few people live near the tops of stratovolcanoes, but the effects of their eruptions are felt by those living at their bases and even tens to hundreds of kilometers away. The appearance and size of stratovolcanoes commonly gives them a prominent place in indigenous populations.

The most viscous and gas-rich magmas are rhyolites. In some cases, the viscosity leads to very slow ascent rates and the gas separates from the magma. The eventual eruption is then a very steep-sided plug, which commonly collapses, sending rock and hot gas laterally as a pyroclastic flow for 1–20 km (e.g., the 1902 eruption of Mont Pelée on the island of Martinique, where an estimated 30,000 people died). In other cases, enormous quantities of rhyolite build up in the shallow crust and erupt in huge explosions lasting days to even weeks, eventually producing hundreds to thousands of kilometers cubed of tephra that spreads for enormous distances (e.g., tephra from the Long Valley eruption in California is 10 cm deep in Kansas, and tephra from the Campi Flegrei eruption in southern Italy is 10 cm deep near Moscow). These eruptions can alter the Earth’s climate for many years and devastate enormous areas. These are rare events—none has occurred during written history, although several

may have affected human development. The eruption of Campi Flegrei around 40,000 years ago may have affected modern human/Neanderthal interactions, and human migration into South-east Asia may have been slowed by the eruption of Toba around 80,000 years ago. The volcanoes that produce these eruptions are large and commonly form basins 5–50 km across, so large populations may live inside the volcano itself. The abundant signs of heat in these areas, such as fumaroles and hot springs, become part of the cultural understanding of nature.

It is surprising to note that despite their reputation, volcanic eruptions are not the great killers they are popularly thought to be. Estimates of volcano-related deaths over the past 100 years or so range from around 80,000 to just over 100,000, or 800–1,000 deaths per year, with only ten eruptions accounting for 80 percent of these fatalities. In contrast, a single earthquake has killed hundreds of thousands of people in a few minutes (Earthquake Statistics—USGS Earthquake Hazards Program <https://earthquake.usgs.gov/earthquakes/browse/stats.php>, accessed November 23, 2017).

Archaeological volcanology in practice

Archaeological volcanology is not a new field—much of the literate world is probably aware of the 79 CE eruption of Vesuvius and the archaeological excavations at the sites of Pompeii and Herculaneum—but it is one that has been transformed since the 1980s. The history of the field can be traced back to sociologist Gilbert White (1945), who was one of the first social scientists to investigate flood disasters and their impact on affected populations. Disaster studies became a primary focus of sociology by the 1970s, with anthropology following several years later (e.g., Hoffman and Oliver-Smith 2002; Oliver-Smith and Hoffman 1999). It was not until 1980, however, with the publication by Payson Sheets of *Archaeological Studies of Disaster, Their Range and Values*, that the roots of archaeological volcanology can be found. Since that time, the pace of research has accelerated as archaeologists and volcanologists began to see the importance of volcanic eruptions and the implications of this research for modern society. The history

of this research has been discussed in several publications and Cooper and Sheets (2012) and Grattan and Torrence (2007) should be consulted for more detailed information.

A wide variety of scientific tools have been used to investigate volcanoes and more tools are now being put into practice as technology becomes increasingly refined. Dating of eruptions is perhaps the most critical area, because human behavior is difficult to positively correlate with an eruption unless accurate dates are recovered. In general, the temporal placement of archaeological sites is easier and more accurate than the associated volcanic eruption, and more recent eruptions are easier to date than older ones. Dendrochronology has played a role in dating volcanoes since the late 1950s. In recent years, tree-ring research has become much more refined and dendrochemistry, which measures volcano-related elemental concentrations in dated tree-ring samples (Pearson et al. 2005), has been undertaken using laser ablation–inductively coupled plasma mass spectrometry (LA–ICPMS), X-ray fluorescence (XRF), and the ratio of strontium (Sr) isotopes. Other methods used to date eruptions include paleomagnetism (similar to archaeomagnetism and used to date lava flows), thermoluminescence, and radiocarbon, potassium–argon, argon–argon, and other forms of elemental decay dating. Archaeological association has been used for years to date eruptions and can be very accurate if dateable artifacts are found within the lava. The use of traditional cultural histories to provide relative (and sometimes very accurate) dates for eruptions is also becoming common, in contrast to earlier research that discarded this information as myth and therefore unreliable. Tephra studies (see *TEPHRA AND VOLCANIC ASH ANALYSIS*), particularly of stratigraphically deposited cinders, have also become common, and tephra is being used for relative dating and, through chemical analysis, to connect tephra to a specific eruption. The type and shape of tephra can also separate primary volcanic deposits from secondary (or redeposited) volcanic deposits, providing insight into the nature of the eruption impact. Isopach mapping of lava distribution and tephra depth can also distinguish areas that were permanently abandoned from areas that may have been abandoned temporarily but were later reoccupied.

From a theoretical perspective, archaeological volcanologists have used both traditional anthropological and archaeological models, as well as borrowed the concepts of “vulnerability” and “resilience” from sociology. Several well-known “disaster scales” have also been published over the years, which list variables that structure both the volcanic eruption and the human response, as well as the psychological impact of volcanoes on affected populations (Bawden and Reycraft 2000). It is anticipated that as archaeological volcanology matures, theory specific to the discipline will be further developed.

Future directions

Archaeological volcanology is a multidisciplinary field that has since the 1980s moved from an interest area for a few archaeologists and volcanologists to a legitimate scientific discipline with a dedicated body of practitioners. The goals of archaeological volcanology research are twofold: (1) to interpret, through the use of archaeological and volcanological methods and theory, the specific eruption and adaptive human behavior that are under investigation; and (2) to provide information to modern hazard and disaster researchers that can help with the planning and management of future disasters. At present, more archaeologists are involved in the field than volcanologists, but that is starting to change as word spreads to volcanologists and as more money is earmarked for disaster research.

Archaeological investigation fits well with this research due to its time depth, its behavioral focus, and its long-standing familiarity with and use of environmental variables. The emphasis by volcanologists on the details of the timing and processes of the eruption complements archaeological goals. Insights derived from archaeological volcanology investigations are now starting to be used by those in the hazards and disaster communities and should continue to increase in the future.

Around 50 volcanoes erupt worldwide every year and almost 1 percent of the world’s population, or around 500 million people, live in areas with active volcanism. Although the occupation

of these areas is partly due to their fertile agricultural soils, it is also a result of population growth, as more people are forced to settle in volcano- and disaster-prone areas. This in and of itself supports the importance of archaeological volcanology as a distinct scientific discipline, serving both as an avenue for research to better understand volcanic eruptions and human behavior, and as a resource that can be used to assist modern hazard managers and disaster planners.

SEE ALSO: Archaeometry; Argon–Argon Dating; Disaster Archaeology; Isotopes; X-Ray Fluorescence Spectrometry (XRF)

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Archaeoseismology

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Archaeoseismology is the study of earthquakes using evidence in the archaeological record. It is one of the disciplines that belong to the broad research field of earthquake sciences, which all share a common goal, that is, to reconstruct the earthquake history within a region with the purpose of assessing the seismic hazard and mitigating the seismic risk. The archaeological evidence for earthquakes comprises chaotic destruction layers, typical damage typologies to manmade constructions, displaced manmade constructions, indications of repairs, sudden abandonment of sites, sudden cultural changes, and so on.

Historically, earthquakes were used in the first half of the twentieth century by archaeological excavators to explain what otherwise could not be explained, at archaeological sites in earthquake-prone regions, such as the Mediterranean. Noteworthy in this respect was Sir Arthur Evans, the famous excavator of the Bronze Age Minoan site of Knossos on the island of Crete (Greece) in the eastern Mediterranean Sea. He was the first to consider earthquakes as the primary destructive agent, leaving clear marker horizons in the archaeological stratigraphy. The early development of archaeoseismology was subsequently grafted on archaeological work in the Mediterranean and Middle East, strongly dependent on identifying structural damage features to monumental buildings at archaeological sites (Stiros and Jones 1996). Earthquakes quickly turned out, though, to be used too easily as a “*deus ex machina*,” provoking skepticism within the community of earthquake scientists, who questioned whether cultural material data could reliably serve as earthquake indicators at all.

The primary challenge of the earthquake sciences is to better constrain the earthquake hazard which a community is faced with today and will

be confronted with in the future. Knowing the earthquake hazard, a community can take the necessary measures to mitigate the earthquake risk—that is, avoiding casualties and limiting damage to housing and infrastructure. The earthquake hazard is expressed as a probability that an earthquake of a certain magnitude or greater may occur, or that a certain level of ground motion may be exceeded, in a well-defined time period. Classically, a 10 percent probability in 50 years infers that the event considered has a return period of 475 years. This practice of probabilistic seismic hazard assessment (PSHA) is primarily based on the principle of elastic rebound. Over long periods of time, tectonic stresses build up in faults to a point that the friction on the fault is exceeded and the fault is activated, suddenly releasing the stored elastic energy, which radiates from the seismic source, causing an earthquake. This characteristic succession of interseismic periods of stress build-up and sudden events of coseismic stress release is known as the earthquake cycle. Another characteristic of active fault systems is a specific correlation between the magnitude of an earthquake and its frequency of occurrence, known as the Gutenberg–Richter distribution. Earthquakes with small magnitudes are rather common, and thus have a short earthquake cycle (months to years), while earthquakes with large magnitudes are rather rare, having a long earthquake cycle (centuries to millennia). To assess future seismic hazard, a reliable estimate of the parameters controlling the Gutenberg–Richter distribution (e.g., *b*-value) is a prerequisite. This can only be achieved by reconstructing the earthquake history in a region in as much detail and as far back in time as possible. However, seismic-hazard practitioners are confronted with the problem that the time window of instrumentally recorded earthquakes is too short; it only spans somewhat over a century. A magnitude–frequency correlation, solely based on a century of instrumental earthquake data, shows in most cases a margin of error, which is too wide to enable a reliable seismic hazard assessment. The archive of earthquakes therefore needs to be extended back in time, calling

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upon all possible evidence for pre-instrumental earthquakes. On the one hand, information on pre-instrumental earthquakes can be found in all types of historical—written—records (historical seismology). On the other hand, paleo-earthquakes leave their marks in the geological and/or geomorphological record (paleoseismology and earthquake geology). In this broad research field of earthquake sciences, reflecting a continuum of overlapping and complementary disciplines, archaeoseismology, focusing on cultural material data spanning the last few millennia, occupies a unique position, bridging the gap between instrumental and historical seismology on the one side, and paleoseismology and earthquake geology on the other. Depending on the time span of occupancy, possibly expanding over one or more earthquake cycles, archaeological sites can provide crucial information to seismic-hazard practitioners.

Another issue seismic-hazard practitioners are confronted with is the nature of the pre-instrumental earthquake evidence. From their perspective, it is imperative to know the physical parameters of each earthquake, brought together in an earthquake catalogue. These parameters include the date of the earthquake, its magnitude, its seismic source, its epicenter, the duration, and the ground acceleration. All these parameters can be instrumentally measured, and are thus known for most of the instrumentally recorded earthquakes. However, pre-instrumental earthquakes can only be parameterized indirectly, based on the evidence found in the historical, archaeological, and/or geological record. This indirect evidence can be split into two categories. On the one hand, there is primary evidence, directly related to coseismic surface rupturing or ground failure. On the other hand, there is secondary evidence, related to coseismic ground shaking and ground motion. The challenge is to translate this indirect earthquake evidence into (semi-) quantitative parameters that can be used in a seismic hazard assessment.

In archaeological contexts, earthquake archaeological effects (EAEs) can also be classified into primary and secondary evidence. Moreover, a third category of earthquake evidence can be distinguished in archaeological and historical contexts—that is, the postseismic, delayed-response effects of an earthquake, such

as fire damage, repairs, recycling of building materials, complete or partial abandonment, and architectural and/or cultural changes.

Two types of primary or secondary EAEs can furthermore be distinguished: structural effects on manmade constructions and stratigraphical effects in the archaeological stratigraphy. While the former effects received the most attention in the development of the discipline, focusing on archaeological contexts with monumental constructions, the latter effects have attracted more interest recently, in particular when focusing on archaeological contexts dominated by rubble architecture.

The most obvious primary structural EAEs are archaeological remains that are displaced due to the coseismic surface rupturing on an active fault. These faulted relics not only enable the identification of active faults in the landscape, but also allow the determination of the type of faulting, the amount of coseismic slip related to a single earthquake, as well as the cumulative fault slip caused by multiple earthquakes during the existence of the displaced manmade construction; knowing the age of construction, a time-averaged fault-slip rate spanning centuries to millennia can be derived. In this respect, the study of faulted relics is very comparable to paleoseismological work. These fault-slip rates obtained from an archaeological context can be compared with slip rates, obtained from paleoseismological and geological contexts on the same active fault. Such comparison may reveal potential slip deficits, inferring a high seismic hazard.

Secondary structural EAEs, caused by coseismic ground shaking and ground motion, comprise typical strain structures in the building fabric. These earthquake-related damage features are most obvious on monumental buildings and constructions. Recognizing such structural damage features in rubble architecture, on the other hand, is a challenge. Coseismic ground shaking can generate a wide range of typical damage features, such as penetrative fractures in masonry walls, rotated and displaced drums in columns, dropped keystones in arches, collapsed stairways, domino-type collapsed walls and columns, and U-shaped gaps in walls. Coseismic ground motion, for example, due to liquefaction, can generate other types of damage features, such as folded and fractured pavements, and

tilted, rotated, and bent walls. All these structural EAEs are assessed semiquantitatively by using modern earthquake intensity scales, which are applied in assessing the earthquake damage caused by recent—and thus instrumentally recorded—earthquakes (e.g., the European macroseismic scale EMS-98). An additional challenge is to unambiguously distinguish damage caused by an earthquake and damage caused by other destructive agents, such as natural failure, storm, vandalism, looting, or warfare. Moreover, it is very difficult to attribute specific damage features to a single earthquake, in particular in earthquake-prone regions, where ancient buildings at archaeological sites have most probably experienced ground shaking from numerous earthquakes over their lifespan and even following final abandonment. The danger thus exists that by attributing damage features that may have been caused by a whole series of earthquakes to a single earthquake, unrealistic earthquake catastrophes emerge, which subsequently may find their way into earthquake catalogues.

The stratigraphical effects of earthquakes is materialized in archaeological destruction layers or deposits, defined as horizons showing evidence of sudden destruction caused by human and/or natural agents, commonly covering a “living surface,” evidenced by, for example, in situ broken vases, buried valuable objects, and/or skeletons of victims. Earthquake-related destruction deposits further contain burned material, charcoal, collapsed architectural debris, and crushed and toppled objects. In archaeological contexts, lacking any structural EAEs, destruction layers may provide the only evidence for ancient earthquakes. Again, relating a destruction horizon to an earthquake is rarely unambiguous and remains a challenge for archaeoseismology. The principal issue with the study of destruction layers concerns the preservation and disturbance of destruction layers. Earthquake debris may have been cleared from streets and buildings and disposed of at particular dumpsites, so that no destruction layer is preserved in the archaeological stratigraphy. Valuables and/or victims may also have been recovered from the debris, while material may have been recycled in rebuilding efforts, resulting in very disturbed destruction horizons. The preservation of pristine destruction layers may therefore depend more on social

factors, such as the degree to which the affected community was able to cope with the aftermath of the earthquake, than on physical parameters, such as the magnitude and proximity of the earthquake. This results in a very incomplete stratigraphical record of earthquakes, which is moreover not evenly distributed through time. This preservation issue concerns not only stratigraphical earthquake evidence but also structural earthquake evidence, resulting in an observation bias in archaeoseismology, focusing on periods of upheaval, destruction, abandonment, and so on.

Constraining the timing of the damaging earthquakes is one of the greatest challenges in archaeoseismology. Chronological control is achieved by bracketing earthquake evidence with a minimum (*terminus ante quem*) and maximum (*terminus post quem*) age. Alongside radiometric dating methods (e.g., radiocarbon dating), archaeological dating tools, based on, for example, architectural styles, ceramic style changes, coins, and inscriptions, are used in constraining the timing of earthquakes. The accuracy and precision of the age control largely depends on the type of dating applied and on whether or not multiple age determinations, using complementary dating methods, have been performed. The main issue with respect to archaeological earthquake evidence is rather poor temporal resolution, ranging from decennia to centuries, making it nearly impossible to pinpoint archaeological earthquake evidence to historical earthquakes. The danger, moreover, exists that ancient earthquakes, poorly constrained in time, are equated with historically documented earthquakes, based on an inherently incomplete earthquake catalogue. When, subsequently, the archaeological earthquake evidence is used as supplementary proof for the historical earthquake, a circular argument arises. Poor temporal resolution may also lead to erroneous interpretations of earthquake evidence as the result of a single oversized earthquake, on the one hand, the sequence of the main shock and its aftershocks, and on the other hand, a clustered series of earthquakes. Finally, poor age constraints hamper the territorial correlation of EAEs between different archaeological sites, again giving rise to the danger of amalgamating earthquake evidence for regionally distinct earthquakes into a single catastrophic earthquake. This problem of regionally

correlating archaeological earthquake evidence also limits our ability to quantitatively assess the physical parameters of ancient earthquakes.

Indeed, the magnitude of a pre-instrumental earthquake is assessed semiquantitatively based on the spatial distribution of secondary earthquake evidence, reflecting variable ground motion intensities away from the earthquake's epicenter. By comparing these earthquake intensity distribution maps of pre-instrumental earthquakes with intensity distribution maps of recent, instrumentally recorded, earthquakes in the same region, a reliable magnitude estimate of pre-instrumental earthquakes can be derived. In addition to the poor temporal resolution of archaeological earthquake evidence, hampering a valid regional correlation, the mapping of secondary archaeological earthquake evidence is strongly limited because archaeological sites are rather sparsely and unevenly distributed. Only in regions with a long and rich archaeological heritage does such regional mapping provide useful intensity distributions, which allow the magnitude of an ancient earthquake to be assessed. There is, though, a remarkable spatial bias that can be advantageous for archaeoseismological work. In earthquake-prone regions, human settlements are often located in the direct proximity of active earthquake faults, in what are called seismic landscapes, that is, landscapes resulting from the cumulative geomorphological effect of successive, surface-rupturing earthquakes. There is an increased likelihood of these archaeological sites having a record of both primary and secondary earthquake effects, caused by earthquake activity on the nearby fault. However, the dominant presence of nearby EAEs also obscures the possible presence of far-field EAEs, making regional correlations of EAEs much more difficult. On the other hand, the absence of EAEs at an archaeological site in a seismic landscape may reveal that the faults in the direct proximity of the site were not active during the occupancy of the settlement.

Before a magnitude can even be derived for an ancient earthquake, archaeoseismology is thus still confronted with a number of challenges. To address these challenges, modern archaeoseismology aims to integrate the principles and practices of a very wide range of sciences, from

geophysics to structural engineering. Such a multidisciplinary approach requires a shared protocol and a standardized methodology (see Sintubin and Stewart 2008 and references therein). In recent years, a clear shift towards more quantitative and multidisciplinary approaches has definitively boosted the use of archaeoseismological evidence in seismic-hazard studies. Quantitative archaeoseismology (Hinzen et al. 2010) focuses on, for example, a forward modeling approach, based on earthquake engineering models applied to ancient manmade structures. Scenario-based earthquake ground motion simulations test realistic earthquake hypotheses to explain structural EAEs in ancient buildings. Such a modeling approach is helped by modern visualization techniques, such as 3D laser scanning (see AIRBORNE LASER SCANNING AND LIDAR), which allow the creation of a quantitative, high-resolution, three-dimensional structural model of the ancient building. Quantitative archaeoseismology not only assesses archaeological earthquake evidence with respect to ground motion parameters and magnitude estimates of ancient earthquakes, but also unambiguously discriminates between damage caused by earthquakes and damage caused by other natural or anthropogenic agents. While this quantitative archaeoseismological practice is very effective on sites with monumental architecture, a more semiquantitative, multidisciplinary territorial approach is more appropriate in archaeological contexts dominated by rubble architecture and associated destruction horizons (Jusseret and Sintubin 2013). This approach starts from the seismotectonic context of the archaeological site, identifying the different types of potential seismic sources, as well as their empirical ground-motion relationships. From an archaeological perspective, a well-documented, high-visibility archaeological context, characterized by distinctive and rapid ceramic changes, which provide a good chronological framework, is required. Subsequently, different earthquake hypotheses are tested in an iterative process, eventually leading to an earthquake scenario that provides the best explanation for the EAEs observed in the archaeological context studied.

Finally, by highlighting how communities in ancient times coped with earthquakes, archaeoseismology can boost earthquake awareness in

present-day communities living near archaeological sites bearing evidence of ancient earthquakes. In this respect, archaeoseismology can be part of public policy to mitigate earthquake risk.

SEE ALSO: Archaeological Fieldwork; Archaeology; Cosmogenic Dating; Dating in Archaeology; Disaster Archaeology; Geomorphological Survey; Ground-Penetrating Radar; Image-Based 3D Modeling; Lidar Data Visualization and Processing; Magnetometry

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FURTHER READINGS

Barley, Rye, and Oats

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Barley

Barley (*Hordeum vulgare* L.) is an important cereal that can thrive in a greater variety of conditions when compared with wheat, including drier and colder environments, poorer soils, and more saline sediments. It is this resilience that supported the spread of barley from the Near East—where it first began to be farmed—and its uptake in many other parts of the world. Barley grains were used in breads, vessel-based stews and gruels, alcoholic drinks, and fodder, while chaff and straw were used in objects and structures.

Domesticated barley (*Hordeum vulgare* subsp. *vulgare*) is among the first crops to be domesticated in the Near East—a founder crop (Zohary, Hopf and Weiss 2012; Fuller 2015). It is likely that barley was growing wild in southwestern to central Asia, as it does today, and these wild progenitors were domesticated. The wild ancestor of barley is thought to be *Hordeum vulgare* L. subsp. *spontaneum* (C. Koch), which can be found around the east-Mediterranean basin and west Asiatic countries. Genetic studies suggest there were several independent centers of domestication for barley, including the Fertile Crescent (a large area that encompasses Israel to western Iran) and further east within the Iranian plateau (Morrell and Clegg 2007).

Even before domestication, wild barley was gathered as a foodstuff (Zohary et al. 2012, 56), for example in Israel at Ohalo II (23,000 BP) and even earlier at Kebara Cave (50,000 BP). Pre-domestication cultivation occurs during the PPNA period (9700–8800 BCE)—a hoard of 260,000 wild barley grains was found at Gilgal, Israel. Over the course of the following 3,000 years, gradual change in the morphology of barley grains and chaff is observed, including

an increase in grain size and in the percentage of non-brittle rachis remains, reflecting domestication. Cultivated barley is recognized by its non-brittle ears, where the spikes remain intact after ripening, enabling harvesting by humans. By contrast, the ears of wild barley are brittle, and at maturity they disarticulate to self-disperse the grains and ensure survival of the plant. Disarticulation scars in wild, brittle forms are often smooth, while in domesticated varieties, threshing results in rough breakage scars.

Barley ears contain spikelets arranged in groups of three alternately along the rachis. The spikelets of domesticated barley are found in a two-rowed form (only the middle spikelet in each group of three is fertile and produces a grain; the two lateral spikelets are grainless) or a six-row form (all three spikelets on each side are fertile and grain-producing). The wild progenitor of barley is a two-rowed form. The six-rowed form evolved under domestication, arising from a genetic mutation that resulted in a failure of the central floret to suppress lateral florets. Wild barleys and many domesticated forms are hulled, where the grain is tightly enclosed by chaff. Naked barleys emerged slightly later, when a single recessive gene caused the hulled trait to disappear, which resulted in grains being looser in the spikelet and easier to process. Early examples of non-brittle, two-rowed barley that are clearly domesticated were found at Tell Aswad, Syria (late 9th/early 8th millennium BCE) and Jarmo, Iraq (later 8th millennium BCE), often as a companion of wheat (Zohary et al. 2012, 56–7). More advanced forms of barley, such as six-row hulled and naked, appear later, during the 8th/7th millennia BCE.

Widespread uptake of barley prompted its movement from southwestern and central Asia to the Aegean region, and subsequently to the Balkan countries, Caucasasia, the west Mediterranean basin and central Europe, western Europe, north Africa, the Indus Valley, and other regions (Zohary et al. 2012; Stika and Heiss 2013). From the 6th millennium BCE, Neolithic societies in

the Balkans, central and western Europe were cultivating barley, often six-rowed and naked forms. Barley reached the furthest margins of western Europe, such as Ireland, soon after 4,000 BCE. By the Bronze Age barley had become more important than wheat in several regions, particularly hulled barley. Barley also spread eastwards to the Indus Valley and Turkmenistan by 6,000 BCE. Barley cultivation in Egypt and along the Nile appears later, around 4,000 BCE. It was after 3,000 BCE that barley began to be cultivated in monsoonal India, and around 2,000 BCE in southern India and China.

Rye

Rye (*Secale* L.) is another cereal whose wild progenitors derive from the Near East, but rye has a very different evolutionary history (Zohary et al. 2012). Nowadays, rye is a staple crop in several regions. Rye flour is baked to produce a dark, dense bread or crispbread/crackers, the grains are used in high-energy animal feed and rye whiskey, the straw in structures and thatching, and the green plants provide early spring grazing. Rye is a relatively tolerant crop that can withstand poor and sandy soils, as well as cold and drought. Rye is unusual among cereals because it is cross-pollinated, which means that its yield is partly dependent on wind pollination, and it disperses pollen more freely than other cereals; for this reason, rye can be over-represented in pollen records (see PALYNOLOGY) when investigating Holocene vegetation change.

Four taxonomic groups of the rye genus have been identified (Zohary et al. 2012, 59–61). The best known is *Secale cereale* L., which contains the domesticated varieties of rye, as well as many weedy races and wild forms. Domesticated varieties are annual free-threshing, nonshattering plants with large, plump grains. Weedy forms of *Secale cereale* are also annuals, found growing slightly to the north of wild stands of barley and wheat, in western and central Asia, and south-east Europe. Other taxonomic groups belonging to rye are the perennial *Secale montanum* Guss. and two annuals, *Secale iranicum* Kobyl. and *Secale sylvestre* Host.

When compared with barley, rye is rather different in terms of its evolution and uptake (Behre 1992; Zohary et al. 2012, 62–5). Early examples of wild rye, presumably gathered, are recorded at Epipalaeolithic Tell Mureybit, Syria (10th millennium BCE). Domestication appears to have taken place in the area around Turkey and Armenia, possibly involving an annual brittle rye (*Secale cereale* subsp. *vavilovii*) or *Secale montanum* Guss., or both. Rye remains that suggest domestication are present at 8th/7th millennium BCE sites in Turkey, such as Can Hasan III and Çatalhöyük East; in the former, relatively plump grains were recorded, as well as nonshattering rachis remains. It is striking, however, that very few remains of gathered or domesticated rye are found in Neolithic and Bronze Age south-west Asia, even though wild forms of *Secale cereale* grow in this region.

Rye migrated to Europe during the Neolithic, perhaps via the Aegean basin and south Balkans, as suggested by finds in Italy and Slovakia, but did not yet become a staple crop. While rye has been found at several Neolithic and Bronze Age sites in central, eastern, and southern Europe, these finds reflect tolerated weeds of wheat and barley crops, rather than rye as a crop in its own right. It is not until the Iron Age–Roman period in Europe that rye appears more frequently and emerges as a staple crop (Behre 1992; Stika and Heiss 2013). Rye is particularly suited to northern Europe because of its winter hardiness, resistance to drought, and ability to thrive on acid, sandy soils. Rye became significantly more important during the early medieval and medieval periods, although historical sources indicate that ergot (*Claviceps purpurea*), a common fungal disease of rye, was a problem in medieval Europe. Rye continues to be grown in Europe and Russia today, as well as North Africa, the Americas, and South Africa. During the twentieth century, a new crop, *Triticale*, was developed by artificially crossing wheat with rye.

Oats

Common oat belongs to the *Avena* genus, which comprises around 25 annual species (Baum 1977; Zohary et al. 2012, 66–7). Several species of oat have been domesticated, but only

one species—*Avena sativa*, common oat—has prevailed as an important cereal. *Avena sativa* comprises many domesticated varieties, including *Avena sativa* in the narrow sense, *Avena byzantina* C. Koch and *Avena nuda* L. Other species, such as *Avena strigosa* Schreb. and *Avena abyssinica* Hochst., persist as minor crops around the world. Common oat is used in flat breads and biscuits, porridges, gruels, and many other vessel-based preparations, including alcoholic drinks.

Common oat shows close genetic affinities and morphological similarities to a variety of wild and weedy oats growing in the Mediterranean basin, including *Avena sterilis* L., *Avena ludoviciana* Dur., *Avena occidentalis* Dur. and *Avena fatua* L. (Zohary et al. 2012, 66–7). Even before its domestication, oat was gathered as a food. Grinding tools in Israel (23,000 BP) and Italy (32,600 BP) have produced evidence for starch grains (see STARCH GRANULE ANALYSIS) of wild oat on their surfaces, suggesting the tools were used to create oat flour. Pre-domestication cultivation has also been recorded at Gilgal, Israel (9th–8th millennia BCE), where a large assemblage of *Avena sterilis* (c.12,000 grains) was found.

It appears that domesticated *Avena sativa* is descended from *Avena sterilis*, but identification of when and where domestication occurred has proved challenging (Zohary et al. 2012; Stika and Heiss 2013; Fuller 2015, 547). Oat chaff—specifically the floret base—is required for secure identification, but the paleoethnobotanical record is often dominated by grains. Grain size is an indicator of domestication, as domesticated grains are usually larger than those of wild relatives, but less reliable than chaff. It is suspected that oat was first domesticated in Europe. Oat is a “trans-domesticate,” whereby its wild ancestral distribution is distinct from the location of domestication. Oat was transported from wild stands, most likely in the eastern Mediterranean region, through human action, moving as a weed of wheat and barley. Oat migrated through Europe during the Neolithic as a backpacker on the actual crops of wheat and barley, and it was not until much later, during the Later Bronze Age and Iron Age, that oat was domesticated. When compared with wheat and barley, oat is well suited to wetter and colder environments, and the presence of these conditions in central and western Europe

enabled oat to thrive. Perhaps on occasions when wheat and barley crops failed, oat began to be harvested as an “emergency” crop, and eventually cultivated as a crop in its own right. Alternatively, oat may have displaced the main crops of wheat and barley where ecological conditions were more suited to oat, and then been taken into cultivation.

Oat is recorded in Neolithic and earlier Bronze Age deposits in Europe, usually in small quantities, but these records are thought to reflect a wild variety. Firm evidence for domesticated oat is found first in Europe, from the 2nd and 1st millennia BCE, for example at a Later Bronze Age granary in Langweiler, Germany. Roman agricultural writers seldom mentioned oat, and where mentioned, it was referred to as a food crop for horses (Ruas and Zech-Matterne 2012). It is not until the early medieval period that oat becomes an important crop in several parts of Europe. This continued to be the case during the medieval period, with oat reaching North America in the seventeenth century.

SEE ALSO: Beverages; Domestication; Environmental Archaeology; Paleoethnobotany; Paleoethnobotany and Ancient DNA Analysis; Wheat

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Beverages

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Beverages, defined here as any type of liquid substance consumed by ancient peoples, are recognized by archaeologists to have occupied important social, political, economic, and religious functions within ancient societies. As food, beverages not only nourish, but can also be used as payment, social lubrication, as a marker of social categories, as a means of preserving food, an important part of ritual activities, or may contain medicine to heal or induce an altered state of consciousness. Beverages are also difficult to recover from archaeological contexts due to the physical nature of liquids. However, evidence for beverages can take several forms reflecting different aspects of human activity, including: organic residues from preparation or consumption, plant remains, historic documents, and ethnographic evidence. Archaeologists collaborate with colleagues in a wide range of disciplines to investigate the production, storage, serving, and consumption of beverages that preserve in the archaeological record. Common analytical methods employed in these investigations include biochemical and paleoethnobotanical analyses.

The use of biochemical analysis has become more widespread in archaeology in recent decades, focusing on plant and animal food residues and chemicals that were absorbed within ceramic vessel walls, including lipids, amino acids, resins, and other organic residues (see ORGANIC RESIDUE ANALYSIS). Two common methods of chemical analysis of beverages within archaeology include high performance liquid chromatography (HPLC) and gas chromatography (GC), which may be used in combination with mass spectrometry (MS) to identify and analyze residues of beverages left behind on ceramic vessels or other artifacts. Combining these two complementary chromatographic techniques with mass spectrometry, archaeologists

are able to separate a sample of organic residue into its individual components, which are then examined for biomarkers of past human activities. For example, liquid chromatography mass spectrometry (LC-MS) has been used to detect compounds associated with Black Drink, a ritual purgative beverage made from parched *Ilex vomitoria* (Yaupon holly) leaves and twigs that are boiled in a pot with water. Indeed, ursolic acid and residues of methylxanthines theobromine and caffeine, considered to be biomarkers for *Ilex vomitoria* plants used in the creation of the ritual Black Drink, were found on ceramic beakers from the Mississippian site of Cahokia near modern day St. Louis, Missouri (Crown et al. 2012). The authors argue that the unique combination of ursolic acid, theobromine, and caffeine, indicates that Black Drink was present in the sampled ceramics.

Cacao (*Theobroma cacao*) was a key ingredient in a variety of ancient beverages, and its detection is of particular interest to archaeologists trained in biochemical methods. Using the fruit of cacao tree that grows in the Mesoamerican tropics, cacao beverages are brewed by fermenting the pulp around the seeds in the pod, drying and toasting the seeds, and then grinding the seeds to add to cold water, possibly with other ingredients including ground maize (*Zea mays*) and chili peppers (*Capsicum annuum*) to create a variety of beverages. The seeds used to make cacao beverages, consumed mainly by elites in ancient times, were widely traded throughout Mesoamerica and were introduced into the American southwest around AD 1000–1125 (Crown and Hurst 2009). Using HPLC coupled MS, the authors identified theobromine, caffeine, and theophylline—three biomarkers that infer the presence of cacao—from dry residues on ceramic cylindrical jar fragments recovered from trash middens near Pueblo Bonito in Chaco Canyon, New Mexico. The presence of cacao residues in these cylinder jars is the first evidence for the trade of the seeds north of Mexico and may indicate that cacao beverages similar to the ones prepared in Mesoamerica were being used in ritual activities in Chaco Canyon.

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Archaeologists trained in biochemical techniques have also studied ancient viticulture (see GRAPES AND VITICULTURE). For example, terebinth (*Pistacia* sp.) resin and tartaric acid have been identified as biomarkers of wine in amphora dating to 500–475 BC in the Mediterranean. Indeed, these studies have not only confirmed that wine was stored in recovered amphorae due to the presence of tartaric acid in the samples, but also provide insight into the ways in which wines were shipped, stored, and used. Compounds detected in imported Etruscan amphorae from central Italy excavated in the southern port city of Lattara in France suggest that herbs, including rosemary (*Rosmarinus officinalis*), basil (*Ocimum basilicum*), and thyme (*Thymus vulgaris*), were added to the grape wine, indicating a possible medicinal role for wine during this period (McGovern et al. 2013). Additionally, compounds from pine (Pinaceae) resin were also recovered from the amphorae, shedding light on preservatives added to the wines for shipping. This particular biochemical study not only illustrates techniques for Etruscan winemaking and trade, but also provides some of the earliest evidence for the importation of wine into France, which is crucial for characterizing the early history of viticulture in this part of the Mediterranean.

The analysis of paleoethnobotanical remains represents another useful method for investigating beverages produced and used in the past. Two forms of paleoethnobotanical remains are available for analysis: macrobotanical (seeds, wood charcoal) and microbotanical (pollen, starch grains, phytoliths). Macrobotanical remains have provided physical evidence for the production of beverages through physical changes in seeds. One way the physical form of the seed may be altered is through the process of malting, which involves soaking and sprouting grain in water to convert starches within the seeds into sugars for fermentation into alcohol (ethanol). Bouby, Boissinot, and Marival (2011) provide paleoethnobotanical evidence for malting at the fifth century AD Roquepertuse (Velaux) site in southeastern France where they recovered a high density of barley (*Hordeum vulgare*) in a state of induced germination. Considering this evidence in combination with the presence

of grinding equipment, ovens, and fermentation pots at the site, the authors suggest that the context represents household-level beer production. Another study demonstrated that wine was produced in Roman southern France at the site of Gasquino, evidenced by crushed grape skins, pedicels (stems), *Vitis* sp. wood charcoal, thousands of pits linked to wine production in fields surrounding the site, and large ceramic containers (dolias) suitable for storing wine that were sunk into the ground. Using multivariate statistics, the researchers found that both wild (*Vitis vinifera* subsp. *sylvestris*) and domesticated (*Vitis vinifera* subsp. *vinifera*) grape varieties were used in local viticulture (Figueiral et al. 2010), providing evidence for the spread and cultivation of grapes throughout the region since the fourth century BC. Archaeologists have also documented that the shape of drupes (fruit seeds) from the molle (*Schinus molle*) tree change from spherical to irregular and lobed when either soaked in water or boiled to extract sugars and flavors for the production of *chicha de molle* (a type of Andean beer). Molle drupes that were either soaked, boiled, or both have been recovered from a brewery located at the Wari regional imperial center of Cerro Baúl in Moquegua, Peru; these data provide evidence for the processing, boiling, and fermenting of *chicha*.

Microbotanical remains are also useful for the study of ancient beverages, especially in contexts where preservation of macrobotanical remains is limited. Using a high-powered polarizing stereoscope or scanning electron microscope, paleoethnobotanists can identify pollen (see PALYNOLOGY), phytoliths (see PHYTOLITH ANALYSIS), and starch grains (see STARCH GRANULE ANALYSIS). In the Andean highlands of the Lake Titicaca basin, maize phytoliths have been used to both track the spread of domesticated maize into the Andes and determine that the probable first uses for maize in the area included the production of *chicha* for ritual purposes around 800–250 BC (Logan et al. 2012). When compared to the abundance of maize phytoliths on grinding stones near ritual spaces, incense burners, and the teeth of sacrificial victims, a lack of maize phytoliths in household cooking vessels suggests maize was first used for ritual purposes rather than for daily household consumption. Additionally, a study

of phytoliths and residues recovered from vessels from Oaxaca, Mexico dating to the seventh century AD documented the presence of maize and theobromine, suggesting that a culturally important beverage in contemporary Mesoamerica (*tajete*, made from cacao seeds and ground maize) may already have a long history of production and storage (Soleri et al. 2013). While the presence of theobromine residues and maize phytoliths in these vessels is not definitive proof that *tajete* was produced during this period, it nevertheless provides a starting point for revealing the recipes of ancient beverages. Further study of the material culture, ethnohistoric literature, and plant remains at this site may yet provide additional evidence for the production of the *tajete*. Finally, pollen recovered from Coptic amphorae from the early medieval period (fourth to seventh centuries AD) site Šarun in Middle Egypt was found to derive from grapes, suggesting wine was stored in these amphorae (Rösch 2005). Some of the samples may have been sweetened with honey, inferred from the presence of pollen from insect pollinated species. The same study found insect pollinated pollen types were present in a mortuary bowl excavated at the late Hallstatt period (800 to 480 BC) site of Niedererlbach in Bavaria, indicating this bowl once contained mead.

While each of these approaches provides supporting evidence that beverages were produced, stored, or consumed in particular archaeological contexts, finding definitive proof for the presence of a specific beverage, or its individual constituents, is difficult. Incorporating multiple lines of evidence, an interdisciplinary approach considering paleoethnobotanical remains, chemical residues, with other artifacts, architectural space, and ethnographic and ethnohistoric materials, provides the best course for investigating and interpreting the production, consumption, and uses of beverages in the past. Additionally, the archaeological study of beverages has not only helped identify the presence of drinks in the past, but it has also contributed to our understanding of their broader political, social, economic, and religious significances. Archaeological studies of beverages can be used to investigate human activities, such as labor, trade, architecture, domestication, medicine, the arts, human diet, and evolutionary biology. Future studies of beverages in archaeology, incorporating multiple

scientific and historical approaches, could contribute an enhanced characterization of beverages in the past, insights into flavors and culinary experiences, and a fuller understanding of our cultural and biological past.

SEE ALSO: Dairying; Drugs and Psychotropics; Food Residue Analysis; Paleoethnobotany

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Biogeography

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With the rise of global trade, plants and animals have found it increasingly easy to move beyond their natural range and, since the early 1800s, the number of “alien species” has risen sharply, with hundreds of exotic plants and animals becoming established worldwide. However, people have purposefully and inadvertently translocated animals and plants for millennia (O'Connor and Sykes 2010; Prance and Nesbitt 2012). Indeed, it is now widely recognized that archaeological studies of plant and animal biogeography can be undertaken as proxy measures of past human migration and colonization (see ZOOARCHAEOLOGY AND HUMAN TRADE AND MIGRATION). Many studies have examined the spread of farming during the Neolithic period (see DOMESTICATION), but biogeographical analysis has the potential to answer a wider suite of questions concerning environmental and cultural change, as well as providing data of relevance to present-day biodiversity management.

In order to gain the above information, and map ancient distributions of plants and animals, identification of archaeological material to species is a necessity. Unfortunately, species differentiation is not always straightforward, especially for closely related taxa (e.g., wild and domestic varieties), and often requires verification by detailed morphological studies, such as geometric morphometrics (see GEOMETRIC MORPHOMETRICS) or genetic analyses (see GENETICS: ANCIENT). Even where identifications are secure, it is important to remember that the bioarchaeological record is the result of human activity and cultural choices. If species are absent from archaeological assemblages, or present only in low frequencies, it does not necessarily mean that they were absent in the surrounding landscape; they may simply not have been exploited by people. Conversely, some species may be

represented archaeologically in areas where they were not present in life, especially if their parts were curated and transported to regions beyond their natural range. For instance, there is debate concerning whether fruit stones found in archaeological deposits represent imported dried fruits or those that were locally grown (see FRUITS, VEGETABLES, AND NUTS). Similarly, animal body parts, for example, skins, antlers, horns, and tusks, were frequently traded as raw materials, medicines, or curios, and, as such, do not reflect the presence of established animal populations.

While trade in plant and animal products is interesting in its own right, it obscures our understanding of ancient biogeographies. Patterns can also be confused by intrusive specimens that have worked their way through the stratigraphy to become incorporated in earlier deposits. Radiocarbon dating of key materials is, therefore, vital to validate interpretations. Other forms of isotope analysis may then help to clarify whether plants and animals were locally raised or imported (see MOBILITY AND OXYGEN ISOTOPES and MOBILITY AND STRONTIUM ISOTOPES). One example where radiocarbon dating and isotope analyses have been combined successfully is with regard to the introduction of the Mediterranean fallow deer (*Dama dama*) to Britain, the timing of which has long been debated. Several Roman sites in southern England have yielded fallow deer remains, and a recent program of ¹⁴C dating indicated that many (but not all) were indeed Roman, dating between the first and fourth century CE (Sykes 2014, 94). By undertaking multi-isotope analyses of these Roman specimens it was possible to demonstrate that the later-dated animals were born and raised in Britain (indicating established breeding populations), but also to identify a first-century first-generation import (see ZOOARCHAEOLOGY AND STABLE ISOTOPES). From where this imported individual derived was hinted at by the DNA analyses of these specimens whose genetics are most consistent with modern Italian fallow deer (Sykes 2014, 94).

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In the case of the fallow deer, it would seem that the widely held assumption that introduced plants and animals were brought by “invading peoples” (here, “the Romans”) was correct. More often, however, the driver for biota diffusion was trade rather than conquest. For example, the numbers of faunal species introduced to Britain are high in periods when the island was well connected to mainland Europe (Neolithic, Bronze Age, Late Iron Age/Roman, and later medieval), but low when trade contacts were poor (Iron Age and Anglo-Saxon). The archaeobotanical record for Britain demonstrates almost identical trends (Sykes 2014, 79).

The arrival of new plants and animals is often interpreted in economic or dietary terms, but it seems that many introduced species were not initially exploited for food; instead they were incorporated into religious practices, often associated with specific deities. In Europe, for instance, the spread of the horse (*Equus caballus*) was mirrored by that of a human–equine divinity, common, albeit in different guises, across Indo-Europe; the brown hare (*Lepus europaeus*) was associated with a less well-known female deity that may (or may not) have evolved into the Anglo-Saxon goddess Eostre, from which Easter takes its name; and fallow deer were associated with the goddesses Diana and Artemis, and the chicken (*Gallus gallus*) with the Roman messenger god Mercury (Sykes 2014, 96–98).

The chicken’s association with the god of travel is particularly apposite, since this species is now the most widespread livestock animal on the planet: a perfect biogeographical case study of human-assisted transportation. As such, the chicken has become the focus of international research as archaeological scientists seek to determine the timing and circumstances by which this culturally and economically important bird spread around the world from its homeland in Southeast Asia. Scientific datasets for different geographical regions are highly uneven, which has resulted in a patchy understanding of the chicken’s diffusion. A synthesis of the available zooarchaeological and dating evidence is presented in Figure 1.

There have been several high-profile studies of the chicken’s eastward spread from Southeast Asia, through Oceania and to the Americas (see

Thomson et al. 2014). These have consisted predominantly of genetic analyses, few of which have given consideration to the cultural, zooarchaeological, or radiocarbon evidence (although see Matisoo-Smith 2015). Generally, all these studies agree that chickens were gradually hopped across the islands of the Pacific during the third and second millennium BCE, taken by people of the maritime Lapita culture who colonized both Near and Remote Oceania (see Matisoo-Smith 2015). The chicken’s arrival in South America was thousands of years later, the earliest radiocarbon-dated evidence suggesting establishment by the fourteenth or fifteenth century CE (Matisoo-Smith 2015, 98). Whether these chickens were brought from Polynesia by the Lapita culture or from Europe by early explorers of the Americas is a more contentious issue, as competing genomic laboratories have generated contradictory aDNA results (see Thomson et al. 2014; Matisoo-Smith 2015). The polemics surrounding these results serves as a reminder that genetic analysis is far from infallible and that interpretations drawn from the data are just that—interpretations—which are strongest when integrated and contextualized with other independent lines of evidence. Genetics alone is not enough (see ZOOARCHAEOLOGY AND ANCIENT DNA).

Until recently, the chicken’s eastward diffusion has attracted little attention, so there are currently few ancient DNA studies or radiocarbon-dated specimens, aside from those presented in Flink et al. (2014): this paper in particular highlights the problems of bioturbation and intrusion in the archaeological record, as one purportedly “Iron Age” specimen returned a modern genetic signature and then, unsurprisingly, a modern ^{14}C date. While the timing of the chicken’s eastward spread is not known precisely, zooarchaeological and cultural data are available, allowing introduction date and fluctuations in population and significance to be estimated (Figure 1). These data are most numerous for Europe, but other regions are beginning to generate important results.

For Africa and the Near/Middle East, two site-specific studies (Perry-Gal et al. 2015; Woldekiros and D’Andrea 2016) have combined radiocarbon-dated zooarchaeological evidence with broader cultural analyses. Through this integrated approach, they have presented compelling hypotheses concerning the timing and

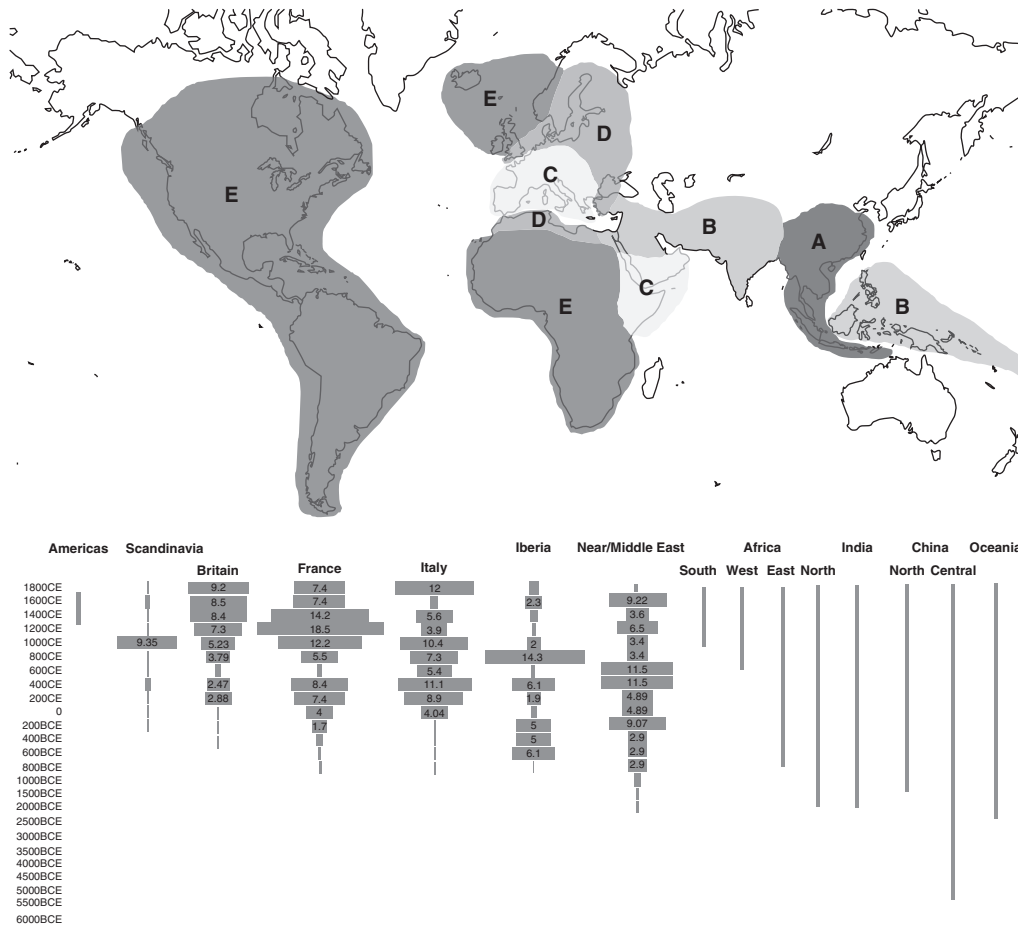


Figure 1 Diffusion of domestic chickens from Southeast Asia. Top: A, earliest domestication in native range ca. 5400 BCE; B, ca. 2000 BCE; C, ca. 900 BCE; D, ca. 400 BCE; E, ca. 600 CE onwards; blank, no data. Source: After Perry-Gal et al. 2015; Woldekiros and D'Andrea 2016; Matisoo-Smith 2015). Bottom: earliest zooarchaeological representation and (where available) changing frequencies (percentage number of identified specimens (% NISP) relative to domestic mammals). Straight lines indicate presence from earliest introduction.

culture-contacts that facilitated the chicken's spread across the regions. The data suggest that domestic chickens formed part of a broader group of plant and animal translocations made by the small-scale maritime communities of the Indian Ocean, which established exchange routes between South/Southeast Asia, India, Arabia, Africa, and the Near East during the Bronze and Iron Ages (Fuller et al. 2011). Evidence from the southern Levant suggests that chickens arrived in the Middle Bronze Age (ca. 2000–1500 BCE) and had become well established by the fourth century BCE, when we have the earliest directly dated

chicken remains from the region (Perry-Gal et al. 2015). For Africa, ^{14}C dating of chicken bones from northern Ethiopia has returned dates of ca. 921–801 BCE (Woldekiros and D'Andrea 2016), and it would appear that they were introduced to the continent via the Horn of Africa, most probably from Arabia.

From these regions, chickens spread around the Mediterranean, arriving in small numbers around 800 BCE. Their initial introduction to northeast Europe and Britain occurred a few centuries later, at about 500 BCE, but it took far longer for them to become established in the

colder climates of Scotland, Norway, and Iceland, where chickens are not apparently present before ca. 800 CE (Figure 1). The climatic requirements of chickens—that they are a warm-loving species—highlights that biogeographical spread is not simply about human will: rates of diffusion are, in part, dictated by physiology, as species often need time to adapt to new environments before they can be moved further still from the conditions of their native range.

The significance of environmental conditions for the establishment of species should not be underestimated, and it may be that the dramatic climatic cooling of the mid-sixth century CE caused the declines in chicken populations seen across much of Europe at approximately that time (Figure 1). Certainly, the Roman-introduced populations of fallow deer, another warm-loving species, appear to have become extinct in northern Europe coincident with the sixth-century cold-snap. Modern British fallow deer populations descending from a second introduction appear to have occurred sometime in the eleventh century CE (Sykes 2014, 96). Fallow deer are not the only species that have been introduced to regions on multiple occasions; indeed, repeated introduction events are likely to be the norm rather than the exception. Fascination with identifying the “earliest” examples of non-native species is, therefore, leading researchers to overlook the subsequent biogeographical dynamics that are often more complex and provide equally rich information concerning past environments and societies.

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Birds

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Birds have been significant to people throughout human history, as seen from depictions in paintings, carvings, and on pottery. Bird remains are an important source of information about relationships between people and birds. Bones, and sometimes feathers and eggshells, show that birds were hunted and kept for many reasons and not just for food. This entry summarizes techniques of bird bone analysis and describes some of the more striking examples of relationships between people and birds. Where no reference is cited, details can be found in the relevant chapters of *Birds* (Serjeantson 2009).

Analysis of bird bones

Until the 1980s, reports on bird bones discussed the significance of these bones mainly in terms of the environment and past distributions. While these factors continue to be important, archaeologists today are more concerned with interpreting human activities. The zooarchaeological techniques used for bird bone study differ in some details from those used for mammals. Bird bones survive in alkaline soils, but only those of large birds are recovered if screening (sieving) is not practiced. Different meshes are appropriate, depending on the species that are likely to be present (Baker and Worley 2014; see also ENVIRONMENTAL ARCHAEOLOGY).

Many species are skeletally similar so to identify bird bones, the zooarchaeologist needs to have access to a comprehensive reference collection. Even the best identification manuals (e.g., Tomek and Bochenski 2009a, 2009b) can serve only as an introductory guide. Some skeletal elements are unfused at hatching and unite later, but in general bird bones do not have separate epiphyses and age estimation is based on bone length

and on the porous appearance of juvenile bone, as shown for chickens by Thomas, Sadler, and Cooper (2016). A sex ratio is not easy to establish. Some birds are sexually dimorphic—for example the bustards (Otidae), in which the males are much larger than the females, and birds of prey, in which females are larger than males. In chickens and other Galliformes, the males have a spur on the tarsometatarsus. Female birds in lay produce medullary bone in the marrow cavity; this is sometimes seen especially in bones of domestic hens. Cut marks, chop marks, and burning are important guides to human activities. It is crucial to take into account the deposition, context and associated finds to fully understand the significance of birds in ritual. Methods of analysis are set out in detail in *Birds* (Serjeantson 2009, 34–98).

Domestic birds

Domestic birds have contributed much more to human diet than wild birds. At least 27 species of birds have been domesticated at some time in the past, and others have been tamed. Some birds were domesticated for their feathers, others as pets. The main domestic birds kept for food are the domestic chicken, the turkey, two types of geese, and two duck species.

Of these, the chicken is the most widespread—indeed, today it is the most successful domestic animal on earth in terms of absolute numbers. Its prehistory is poorly known. Its ancestor, the wild jungle fowl (*Gallus gallus*), which is now virtually extinct, occupied the foothills of the Himalayas. From there it spread north to China, south to the Polynesian archipelago, and west—through Afghanistan, Iran, and the Middle East—to the Mediterranean and East Africa (see BIOGEOGRAPHY). The first domestic chickens were used in rituals, which included cockfighting. In ancient Greece and Rome chickens were often chosen for sacrifice in temples, cemeteries, and also in domestic contexts. Later they were kept for meat and eggs. Three characteristics of chicken bones are guides as to how

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chickens were being exploited in the past: the sex ratio, the age at death, and the prevalence of medullary bone in laying hens. By the middle of the first millennium BCE chickens were being kept intensively for food (Perry-Gal et al. 2015). In medieval Britain, between the eleventh and the sixteenth centuries, there is a contrast between wealthy households with many immature birds and urban areas where more bones come from adult hens.

The natural range of the domestic turkey (*Meleagris gallopavo*) extended throughout central and northern Mexico and the eastern and southwestern United States. Bones from Preclassic Maya sites show that the turkey had spread beyond its original range by the beginning of the first millennium CE. Its domestic status was confirmed through aDNA and morphological analysis (Thornton et al. 2012). Like the chicken, it was not kept merely for food, but also for its feathers.

Two goose species have been domesticated: the greylag (*Anser anser*) and the swan goose (*A. cygnoides*). The first was domesticated in Eurasia, the latter in East Asia. Greylag geese do not reproduce as prolifically as chickens, but the feathers were highly valued. In medieval Europe quill feathers were used as writing implements and the down is still collected today. When the ulna and carpometacarpus—that is, the wing bones to which the feathers are attached—are found in large numbers, we can infer that they were collected for the quills. Geese naturally moult and grow two sets of feathers each year, so geese were kept for this secondary product.

The two duck species that have been domesticated are the wild mallard or common duck (*Anas platyrhynchos*) and the Muscovy duck (*Cairina moschata*). The initial domestication of the common duck may have taken place in Asia or Europe, as this species coexists commensally with people throughout its range there. It was domesticated from about the first century BCE, or possibly earlier. The Muscovy duck comes from Central America and the northern part of South America and there is dispersed evidence for its domestication from the first millennium CE.

Wild birds

People have been catching wild birds since the Middle Pleistocene, but remains are so scant that birds could never have been a regular source of food. It is only from Upper Palaeolithic times that any systematic exploitation of birds began; in periglacial regions of Europe the ptarmigan was sometimes caught using snares, a method also used for small game.

The only people who have relied on wild birds for food were groups who colonized new environments, especially islands. They encountered breeding birds unaccustomed to predation. Invariably exploitation wiped out the breeding population after a few years, and people changed to catching more sustainable prey. The most dramatic example is New Zealand, where large land birds, the moa, had evolved. After the Polynesians colonized the islands they exploited the moa heavily and the birds were wiped out within 200 years (Worthy and Scofield 2012).

The role played by wild birds in human foodways has been greatest at high latitudes and on islands. This is evident in Patagonia, northern Canada, Greenland, and the North Atlantic islands. The most profitable birds to target were those that bred in large colonies, from which they could be harvested at one season of the year. This mode of exploitation was often sustainable, though it brought about the local extinction of some colonies and the extinction of the flightless great auk (*Pinguinis impennis*). The main species targeted were from the shearwater, cormorant, gannet/booby, and auk families. These birds are nutritionally rich because their bodies have a high percentage of fat.

Communities that lived near wetlands often exploited waterfowl, especially ducks, geese, and coots, although, weight for weight, these birds are less nutritious than seabirds. Geese and ducks were caught when they congregated in flocks at moulting time and their flightlessness prevented them from escaping. Once falconry became popular in medieval Europe (see below), the consumption of wild birds became an emblem of wealth and status rather than a matter of survival.

Feathers

The feathers of wild and of domestic birds have been sought after for their decorative as well as for their useful qualities, especially in the tropics, where many birds have a vivid plumage. Feathers were worn by shamans and other spiritual leaders, to symbolize their ritual authority. Feathers themselves survive only under particular conditions: in anaerobic sediments, in conditions of extreme cold, as in northern Canada, or in arid environments. The identification of feathers from their morphology is a specialized skill that will be facilitated by the development of aDNA and ZooMS (Stewart et al. 2013).

From the modified wing bones of crane (*Grus grus*) at Catal Huyuk it was deduced that the feathers had been worn, probably for dances that imitated the crane's nuptial dance. Some birds were domesticated for their feathers alone. The scarlet macaw (*Ara macao*) was domesticated in Mexico and the southern part of the United States: breeding in captivity was confirmed at Paquimé, in Mexico, where isotopic analysis of the bones showed that the macaws had been bred locally rather than procured from their natural range further south (Somerville, Nelson, and Knudson 2010).

Cockfighting and falconry

Some pastimes involve birds: historically, the most significant were cockfighting and falconry (hawking). Cockfighting has a long history in Asia, Europe, and the Americas. In the wild, roosters fight to breed with hens, and this natural behaviour was encouraged. Fights were staged to foretell the outcome of battles and other events and to teach the virtues of aggression in battle. Where greater numbers of male birds than would be expected are present in a domestic flock, this can suggest that cockfighting was the main reason for keeping the birds (Sykes 2012).

For centuries, falconry was an important means of displaying status, both in the Middle East and in Europe. It began in the first millennium BCE in Asia and spread to Europe and the Middle East in the first millennium CE. Falcons are not usually bred in captivity but

are captured in the wild, and their training is a highly specialized skill. Evidence for falconry comes from remains of the raptors themselves, and also from their typical prey species: each raptor was set to fly at prey of a certain size. As it is possible to identify the sex as well as the species of raptors, it is also possible to identify the social rank of the individual who owned the bird.

Symbolic significance of birds

Zooarchaeological evidence that birds had symbolic value for people is elusive, but occasionally it can be found. A bird regarded as a totem animal might be depicted but would not be killed. In many societies, birds were associated with the gods. In Egypt some were tamed and mummified. Birds in flight were regarded as messengers between the gods and humans; for the Romans, the flight of birds foretold the future. All over the northern hemisphere the raven and the crow were seen as birds that communicated with the gods through their power of imitating human speech, and for this reason were taboo as food. They could be tamed and were the ritual companions of shamans or powerful men in northern Europe in the first and early second millennium BCE.

Future

The ability to identify bird bones and feathers from their chemical signature (ZooMS) is going to transform our understanding of birds in the past. This technique also assists the identification of eggshell (Stewart et al. 2013), something that has been difficult until now. The analysis of aDNA will continue to contribute to separating species and was successful with the New Zealand moa. Stable isotope studies reveal ancient as well as modern migration and movements. So long as the study is approached with archaeological and anthropological goals, the range of insights that can come from bird bones is surprisingly wide, especially in view of the relatively small number of bird bones found on most sites.

SEE ALSO: Domestication; Humanity and Animality; Zooarchaeology; Zooarchaeology and Ancient DNA

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Cattle

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Cattle have been among the most important animals for humans for hundreds of thousands of years. Alongside the domestication of the pig (*Sus domesticus*), sheep (*Ovis aries*) and goat (*Capra hircus*), that of cattle was a vital part of what is known as the Neolithic revolution, which saw a shift from hunting and foraging to agriculture. This transition has enabled humans to selectively breed cattle populations for different products such as meat, milk, and labor and to genetically “improve” their stock in order to increase and specialize production and sustain herds.

The aurochs (pl. aurochs, or more rarely aurochsen; *Bos primigenius*) is generally considered to be the extinct wild ancestor of domesticated cattle. This wild species first appeared during the Pleistocene and finally became extinct in 1627, when the last animal died in Poland. The exact origins of the aurochs are not clear; it is thought to have Indian ancestry, being possibly related to *Bos acutifrons*, which dates back to 2 million years ago and lived in the Siwalik Hills of northern India, and also to two other Asiatic species, *Bos planifrons* and *Bos namadicus*. Aurochs remains in Europe have been studied more intensively than remains in other areas, owing to their frequency across the continent and to a tradition of research there. Owing to the long history of the aurochs, their remains have been of interest to paleontologists as well as to zooarchaeologists and biomolecular archaeologists.

Paleolithic and Mesolithic humans regularly hunted aurochs alongside red deer (*Cervus elaphus*) and wild boar (*Sus scrofa*). The geographical distribution of the aurochs fluctuated with the changing climate, as populations retreated to southern areas during cold periods, but at its peak aurochs could be found anywhere from the Atlantic coasts of Europe to the Pacific coasts of

China, as well as in North Africa. No remains have been found in Ireland, which makes the west coast of Iberia the westernmost extent of the range. There is no evidence of the species having crossed the Bering Strait into America. Morphometric study has revealed that the body size of the aurochs varied geographically within Europe, aurochs in northern areas having on average a larger body size than in southern areas during both the Paleolithic and the Mesolithic, in line with thermoregulation (Wright and Viner-Daniels 2015).

The aurochs is thought to have lived in predominantly forested areas. Pollen analysis has shown that most of its distribution area was forested and that it survived longest in the forest landscape of Bialowieza, in east Poland. Additionally, studies of nitrogen and carbon isotopes (see ZOOARCHAEOLOGY AND STABLE ISOTOPES) from Danish aurochs remains have indicated that this animal had a diet with high ¹⁵N values and low ¹³C values—a pattern in line with feeding on litter from the forest floor (Noe-Nygaard, Price, and Hede 2005).

Almost all modern domesticated cattle (see DOMESTICATION) can be attributed to two recognized forms—the humpless taurine cattle of Europe, west Africa, and northern Asia (*Bos taurus*), and the humped zebu cattle of southern Asia and Africa (*Bos indicus*)—and the aurochs is thought to be the wild ancestor for both. A combination of zooarchaeological, genetic and isotopic studies has contributed to the discussion surrounding where and how cattle were domesticated and how the domestic form spread across the world.

It is now generally agreed that there were two independent domestications of cattle worldwide; one resulted in a lineage that included *Bos taurus*, which most likely appeared in the Near East more than 10,000 years ago, and the other contained *Bos indicus*, which appeared on the Indian subcontinent a little later (e.g., Loftus et al. 1994; Troy et al. 2001; Chen et al. 2010). These two species are thought to have been moved by humans respectively across Europe and across

Asia and Africa, with limited interbreeding with local wild aurochs along the way.

The identification of wild and domestic cattle bones has been integral to the debate around cattle domestication, as correct identification can indicate the presence of the wild form, the dispersal of domesticates, and, through this, the pattern and chronology of domestication events. There are very few morphological differences between the two species, but the process of domestication led to a reduction in body size; as a result, morphometric methodologies have long been employed in order to distinguish the species from each other. There is, however, a size overlap between wild and domestic forms that is related to sexual dimorphism: in other words, small female aurochs may overlap with the larger domestic males. Additionally, geographic variation in body size, particularly in wild cattle, has also complicated the distinction between wild and domestic forms. Nevertheless, our understanding of these issues is improving, and biometrical data combined with other zooarchaeological information on age profiles and sex ratios have enabled archaeologists to identify the earliest evidence for cattle domestication in the Near East and to track the movement of domestic cattle across Europe.

A growing body of genetic work (see ZOOARCHAEOLOGY AND ANCIENT DNA) has also been employed to investigate cattle domestication. Most of this work has dealt with mitochondrial DNA (mtDNA). The basis for this work has been the identification of a domestic *Bos taurus* haplogroup “T,” which can be further divided into subgroups T, T1, T2, T3 and T4, and a wild *Bos primigenius* haplogroup “P.” A different haplogroup, named “I,” has been found in *Bos indicus*, which has two sub groups, I1 and I2. Extensive work on the domestication of European cattle, however, has identified a number of other potential *Bos primigenius* haplogroups (e.g., Q and E), indicating that the situation is more complex than originally thought. Further work on mtDNA alongside an increasing number of studies that look at nuclear DNA is likely to further our knowledge in this area in the future.

The domestication of cattle, as that of other farm animals such as caprines (see SHEEP AND GOATS) and pigs (see PIGS), allowed humans a degree of control over a population that could

then be bred to achieve particular selected traits. Both wild and domestic cattle have been exploited by humans for their meat, but domestic populations were also bred for “secondary products,” which can be procured from an animal while it is still alive. It is now clear that domestic cattle were being exploited for both milk and labor from an early date after domestication, and that these are therefore not recent innovations.

Numerous scientific techniques have been used to investigate what products domestic cattle populations were exploited for. Zooarchaeologists use mortality profiles, where models representing typical meat, milk, and traction economies (Legge 1981) are used to aid interpretation. This information should be combined with other zooarchaeological data in order to provide a more reliable interpretation. A typical dairying population (see DAIRYING), for example, is thought to have a high peak of young (predominantly male) calf deaths along with an aging population of predominantly female animals. A population of cattle killed mostly at an older age may indicate that this is a population used primarily for its labor, but this interpretation is much stronger when combined with pathological evidence linked with the impacts of mechanical stress.

Cattle populations have also been “improved” at various points during history, through the inbreeding of newly imported and larger cattle types. A typical example can be seen during the expansion of the Roman Empire across Europe (from the first century BCE onwards), when new, larger Roman cattle were transported to new areas, where smaller Iron Age cattle had previously been dominant. The presence of these large cattle is detectable through analysis of measurements taken on both bones and teeth, as part of zooarchaeological study. This presence has been used as evidence for the process of Romanization, and therefore has wider implications for studies of the spread and extent of Roman influence. The introduction of so-called improved breeds has been detected, with the help of these techniques, in a wide variety of individual contexts and also across broader timescales, which can be linked with agricultural innovations. A notable example is a size increase in cattle, and indeed in other livestock, in Britain, from the sixteenth century onwards, a phenomenon attributed to a shift in

agricultural practices that led to the agricultural revolution (Davis 1997).

Zooarchaeological study can be supplemented by targeted biomolecular work in order to give us a clearer picture of the mechanisms of cattle improvement and their links to cultural change. In the case of Roman Britain, for example, evidence from strontium isotope ratios ($^{87}\text{Sr}/^{86}\text{Sr}$) in cattle tooth enamel from the site of Owlesbury indicated growing diversity in the geographical origin of cattle during the Roman era by comparison to the preceding Iron Age, which correlated with an increase in body size seen through the biometrical approach and with other evidence for the opening up of the trade network (Minniti et al. 2014).

Cattle have continued to be exploited for a variety of different products down to the present day; such products include beef, veal, dairy and leather and they have great economic and social importance across the world. The domestication of cattle was one of the most significant agricultural innovations ever achieved by humans, but it is sometimes easy to forget that our relationship with this animal goes back much further in time and that cattle are in fact more ancient than our own species. We would do well to remember not to take these animals for granted and to view their modern exploitation critically.

SEE ALSO: Zooarchaeology

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FURTHER READINGS

Caves and Fissures

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Caves, rockshelters, and fissures are a unique group of geomorphic features in that they are, in part, defined by their accessibility or functional role with respect to humans. Gunn (2004, Editor's Introduction) defines caves as "natural openings, usually in rocks, that are *large enough to permit entry by humans*" (emphasis added). Likewise, rockshelters can have many morphologies, but must always afford their occupants some degree of protection from the elements. Caves and rockshelters are also sometimes distinguished by dimensions and lighting: Caves are deeper than they are wide and have unlit zones, while rockshelters are wider than they are deep. Fissures lack roofs, and are predominantly vertical in orientation, but are still of significant size that humans or their livestock might fall inside. The term "cavity" can be used to describe any type of cave, shelter, or fissure.

Several classification systems exist for both caves (White and Culver 2012) and rockshelters (Mentzer 2016). Typical approaches include grouping by formation process, bedrock, and morphology. For archaeologists, knowledge of classification systems is useful for understanding how people might have used cavities, and how the morphology, bedrock composition, microenvironment, and other occupants may have contributed to deposition, erosion, and preservation of archaeological materials. For example, deep cave systems formed in limestone can contain multiple types of archaeological sites ranging from deeply buried occupation debris in moderately lit entrances, to surface finds of ritual deposits in the dark recesses. Alkaline dripwater and calcareous speleothems—which contribute to preservation of archaeological materials such as wood, ashes, and bone—are

most common in karstic systems, but have also been documented in sandstone sea caves and basaltic lava tubes. Vertical shafts, such as those found in fissure caves, pit caves, and dolines accumulate archaeological materials and human remains as a result of passive movements (e.g., erosion, accidental falls) or active discard (e.g., waste dumping, murder).

As features that are by definition accessible to humans, it is not surprising that our species and its ancestors have utilized caves, rockshelters, and fissures in many ways. These features have particular significance in paleoanthropology, because cavities have geologic longevity and functioned as natural sources of shelter and also traps where skeletal remains could accumulate (Dirks and Berger 2013). During the Early and Middle Pleistocene, cavities became repositories for a significant number of skeletal remains due to accidental falls, suffocation, or hunting and scavenging by carnivores. Even in the Late Pleistocene and Holocene, cavities remain valuable find localities. A majority of Neanderthal remains and the earliest anatomically modern humans recovered outside of Africa were discovered in caves. *Australopithecus sediba*, *Homo floresiensis*, *H. naledi* and the Denisovan subspecies are known only from remains found in caves.

Beginning in the Lower Paleolithic, hominins also utilized cavities as sources of shelter, water, and raw materials. Middle and Upper Paleolithic people diversified their uses of caves to include localities for burial, ritual behaviors, and parietal art. In the Neolithic, humans began using cavities as stables for livestock, developing maintenance behaviors such as seasonal clearing, foddering, and finally burning of accumulated dung which produces a deposit known as *fumier*. Cavities have also been used as crypts, storage areas, waste repositories, mines for mineral resources and guano, quarries, and recreational exploration. Unique microenvironments make some cave systems well suited for the storage of perishable materials, with some functioning as natural refrigerators or desiccators. For example, the dry caves of North America have yielded a rich record

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of perishable organic artifacts, including shoes, baskets, and clothing. Humans also construct architectural features in cavities, ranging from windbreaks and gateways to entire structures or villages (e.g., cliff dwellings of the American Southwest). Humans continue to use caves for habitation today, and ethnographic observations of use of space and material discard patterns have helped inform our interpretation of the archaeological record.

Scientific analyses can be applied to any archaeological materials recovered from cavities; however, there are some approaches that require specific consideration of the cave environment. These include the study of site formation processes, geochronology, remote sensing, and paleoenvironmental reconstruction. Several archaeological science techniques described below were either first applied in cave and rockshelter settings, or were specifically developed in order to address research questions that are unique to these types of sites.

Site formation processes

The most common application of archaeological science to cave and rockshelter sites is the study of formation processes of the features themselves coupled with a reconstruction of infilling, and sometimes erosion (see GEOARCHAEOLOGY and FORMATION PROCESSES). Comprehensive summaries of cave and rockshelter geoarchaeology are provided by Farrand (2001) and Goldberg and Sherwood (2006). Geoarchaeological approaches include both field and laboratory analyses. Documentation of the stratigraphy, expedient estimation of sediment texture, description of color and visible inclusions, and acid tests are carried out during, or immediately following excavation, and can aid in grouping archaeological materials by sedimentary unit. Laboratory analyses are conducted with the aim of further describing sedimentary units, correlating units across the site, and identifying sediment sources and postdepositional processes and include particle size analysis, calculation of calcium carbonate abundance, and micromorphology (see MICROMORPHOLOGY). Some analyses, such as measurements of elemental abundance using

X-ray fluorescence, and identification of primary and secondary minerals using Fourier transform infrared spectroscopy (FTIR; see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)) can be conducted in both the field and laboratory. The latter technique was specifically developed for the study of diagenesis (see DIAGENESIS OF BONE) in caves (Karkanas et al. 2000).

The main sources of sediment in caves and rockshelters can be classified into autochthonous and allochthonous, while modes of sedimentation can be geogenic, biogenic, and anthropogenic (Farrand 2001; Goldberg and Sherwood 2006). Autochthonous sediments derive from within the cave system. An example of a geogenic autochthonous sediment is a layer of bedrock fragments derived from roof collapse (*éboulis*), while an example of a biogenic autochthonous sediment is bat guano. Both of these sedimentary facies are unique to cave, rockshelter, and fissure settings. Allochthonous sediments derive from outside the cave system, and can range from silts with an aeolian (geogenic) mode of deposition to clay floors of anthropogenic origin. Reconstructing the source and mode of deposition is one of the first steps in understanding the formation history of an archaeological site, and can lead to further avenues of investigation. For example, *éboulis* layers can mark the location of former overhang positions, which aids in modeling the morphology of the cave or shelter over time. The identification of guano in a site has implications for the timing of human occupation relative to other animals, the preservation of archaeological materials, and even the possibility of recovering paleoenvironmental indicators.

Although soil-forming processes can and do impact sediments within caves and rockshelters, the expression and intensity of postdepositional weathering can be very different compared to open air sites. For example, clay translocation can be spatially constrained due to the presence of dripping water along the brow (the so-called dripline) and bedrock joints. Dripwater and pore water have more variable composition within cave environments, ranging from strongly acidic to strongly alkaline depending on bedrock composition and the presence of sedimentary components such as guano or wood ash.

In cave environments, secondary cementation of sediment can yield a cave breccia that on one

hand aids in the preservation, but on the other hand can make excavation exceptionally difficult. Some strategies for dealing with these types of deposits include drilling, jackhammering or controlled explosions which allow archaeologists to remove large blocks for more careful excavation in a laboratory setting. This approach has been utilized for a number of sensitive skeletal remains, including Australopithecines from the Sterkfontein caves of South Africa.

There is much focus in the archaeology of caves and rockshelters on sedimentation and postdepositional alteration, which leads to the generalization that caves and rockshelters are sediment traps. The mode and intensity of erosion (see *EROSION*) from these types of sites is dependent on the geomorphic setting. Cavities located in coastal and fluvial regimes can be inundated and eroded by water; changes in base level in the same settings can also initiate slope instabilities outside of the cavities, resulting in colluvial movement. Erosion of deposits can also occur within cave systems as a result of sinkhole formation and slumping, or internal and external breaching of bedrock. Even cemented sediment can be impacted. Weathering of breccia and formation of new cavities within is a process that characterizes many of the sites in the Cradle of Humankind (see Dirks and Berger 2013).

Imaging techniques

As described above, archaeological excavations in caves are made difficult by some components of cave sediments, such as large blocks of bedrock and cave breccia. In some cases it is useful to have prior knowledge of the sediment depth and composition prior to testing. Penetrometers have been employed in order to obtain rough estimates of sediment depth (see *SOIL PENETROMETRY*). Ground-penetrating radar (see *GROUND-PENETRATING RADAR*) has the additional advantage of being able to image subsurface sedimentary layer boundaries in addition to bedrock topography. The complex morphology of some cavities can also prevent more typical approaches to mapping sites. In these cases, modeling of caves, rockshelters, and fissures can be achieved using laser scanning (see

LASER SCANNING), LiDAR, and photogrammetry (see *IMAGE-BASED 3D MODELING* and *LIDAR DATA VISUALIZATION AND PROCESSING*). These approaches have the advantage of generating three-dimensional models that can then be used to produce views of the entire cave system or specific areas of archaeological significance.

Dating techniques

Nearly any dating technique can be employed in cave and rockshelter settings, although some caveats may apply. For example, in cave sites, uncertainties in modeling changes in environmental radiation can negatively impact the precision of ages produced by optically stimulated luminescence (see *OPTICALLY STIMULATED LUMINESCENCE*) and electron spin resonance (see *DATING AND ELECTRON SPIN RESONANCE (ESR)*). Likewise, ongoing weathering of bedrock and complicated infilling and erosion histories can make cosmogenic dating (see *COSMOGENIC DATING*) more difficult compared to open-air settings. Conversely, cave systems can be ideal locations for the application of uranium-series dating (see *URANIUM-SERIES*), as speleothems may form within or on top of archaeological deposits.

Paleoenvironmental reconstruction

In the 1960s–80s archaeological research on caves and rockshelters was dominated by regional studies that attempted to correlate deposit types with broad paleoclimatic conditions. In French Paleolithic sites, *éboulis* layers were attributed to cryoclastic processes during glacial periods (see Laville, Rigaud, and Sackett 1980). More recent work on this topic, summarized by Woodward and Goldberg (2001), emphasizes that while individual cavities may preserve deposits indicative of local environmental conditions, regional correlations are problematic and best avoided. Nevertheless, some paleoclimatic studies can provide information about the immediate local environment with a high degree of chronological control. Measurements of stable isotopes of oxygen, carbon and hydrogen; major and trace elements; and even sediment inclusions can be conducted on laminated speleothems, such as stalagmites, with chronology provided by uranium-series or

radiocarbon dating. The Pinnacle Point complex of South Africa is one example of a cave and rockshelter cluster that contains a speleothem record in addition to several contemporary archaeological sequences. Other types of local archives in cave sites include sediment containing magnetic particles, diatoms, pollen, microcharcoal, and other environmental proxies. Some deposits, such as lacustrine sediments and guano have the potential to yield records with an annual scale of resolution. Finally, geoarchaeological analyses of sediment can reveal fabrics, structures, and microstructures, such as ice lenses, that have significance for local climatic conditions at the time of formation.

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Charcoal and Wood Analysis

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Wood and charcoal analysis provides us with the tools to examine ancient wood cultivation and consumption habits, and contribute to understanding ancient economies. Almost any type of wood was used as fuel and virtually all types are found in the archaeological record. “Preferred” woods in Europe were (dried) hardwoods, such as oak, beech, maple, and hornbeam. In the tropics, a range of woods were available from coastal mangroves to forest hardwoods, many from the Dipterocarpaceae family. European hardwoods provide a fairly similar average calorific (heat) potential, while tropical hardwoods are, on average, denser and can potentially supply more calories for the same weight.

European hygrophilous woods (those living close to water such as alder), have a lower average calorific potential because of their higher water content. Water needs to be driven off before the calorific value of such woods can be realized. This is true also of tropical wood types. If woods with an inferior lower calorific potential are employed, then a greater quantity of the wood will be required to achieve the same temperature, all other factors being equal. Drier climate woods often found in Mediterranean climes, called “macchia” or “macquis,” make good fuel although they often consist of small and prickly branches that are difficult to collect, and often produce unpleasant smoke.

Preferred timber woods were usually those deciduous and evergreen hardwoods that produce long and strong planks, especially oak in Europe and teak or ebony in the tropics. However, in shipbuilding, conifers such as silver fir, high altitude mountain pines, and cypress occur in the archaeological record. Cedar, while recorded in the ancient literature, especially in Egypt, and

the Eastern Mediterranean, is yet to be found archaeologically in any quantity other than for sarcophagi, and funeral furniture. This is most probably due to limited work on shipwrecks from these areas.

Collection of fuel woods by ancient peoples has often been interpreted as being governed by the “Principle of Least Effort” (Shackleton and Prins 1992). However, recent research shows that even in early prehistory, woods may have been collected according to their calorific value, or perhaps for other social reasons. From broadly 3300–1200 BC, selectivity increases, along with the use of charcoal as a fuel.

Wood in the archaeological record

Wood may be preserved in the archaeological record in several forms: petrified (usually pre-Paleolithic), mineral-replaced (where salts replace the wood structures), mineral preserved (where preservation occurs due to the effect of metal corrosion products (see FORMATION PROCESSES), desiccated (especially in parts of Asia, Africa, and the Aegean), wet (in anaerobic conditions, for example in Northern Europe), and charred. The latter two forms of preservation are the most common and require slightly different approaches to analysis.

Wet woods are analysed while still wet, that is, before conservation. Whole timbers are collected, or samples are taken, usually by a specialist. Identification proceeds after the sectioning using a microtome or hand blade, followed by mounting on slides. A cryotome (which freezes the sample) may be used for sectioning fragile material. Three sections in different planes are required for identification: transverse (“across” the grain); longitudinal (“down or with the grain”); and radial (longitudinal, following the round of the wood).

Collection of charred wood (charcoal) takes place during excavations, as for other material culture. Collection using dry sieving is preferable. Flotation, undertaken for the collection of seeds, microfauna, and other small items, is less

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helpful for archaeological charcoal as it leads to fragmentation. Experiments have established that the fraction >4 mm provides the best results in terms of representation. Collection strategies up to now have focused on primary deposits such as hearths, ovens and so on, but these provide only a limited view of the last, or last few burn events. Randomized, but systematic spatial and temporal sampling (see SAMPLING IN ENVIRONMENTAL STUDIES and SAMPLING THEORY) is preferable to obtain an overall view of the woods consumed for a particular time period and location. After consulting the stratigraphic record, auditing of charcoal preservation levels, and gaining an understanding of the reporting goals for the site, the wood and charcoal analyst is able to make decisions about the quantity of identification work required. Frequency curves are used to determine sampling adequacy. These plot the number of fragments (x axis), against the unique number of taxa identified (y axis). As identification proceeds, fewer unique taxa will be discovered. A “saturation point” is often reached at about 20 percent of the fragment count (where about 80 percent or more of the unique taxa will have been discovered). The curve observed is usually a steep “S.” After this point, the majority of the taxa will have been found, and so identification can conclude and the optimal fragment count for the assemblage gauged. For areas of low floral diversity (for example, Roman Britain), examining around 50–100 charcoal fragments per context can prove sufficient, while for the Mediterranean, where diversity is often higher, 250–350 fragments are more commonly examined per time period or context. Specialists review the optimal fragment count required during analysis, especially if changes occur in wood type or size as new contexts are examined.

Charcoal may be fractured by hand, or using a scalpel, to produce sections in three planes as for wet wood. Both wet and charred woods retain most of their cellular structures even after long-term deposition, and so identification under a compound microscope (x10–x400), can often be made to species level, although resolution to genus or only family level are common. Modern reference collections, as well as atlases, assist identification (Wheeler and Brown 2004; Schweingruber 1990). In addition to species identification, analysts also make observations about

presence of mineral and other inclusions which can relate to preservation conditions, cultural use, or both (see TAPHONOMY). For example charred *hyphae* can indicate the use of dead or cropped wood, while uncharred *hyphae* demonstrate postdepositional fungal damage.

Estimation of wood diameter and curvature are employed to analyze cropping and management strategies. Wood remains must be around 4–5 mm in cross-section for measurement to be possible. Curvature is usually classified according to a scale from straight—no or low curve—indicating the use of “large” wood, perhaps over 50 cm in diameter, to highly curved, indicating the use of twigs and small branches (Marguerie and Hunot 2007). Diameters may be estimated if a specimen retains both the pith and bark, although allowance for shrinkage from the charring and burning process must be made. Charred woods shrink from 10–25 percent depending on size of the original branch and type of wood. Diameters can be estimated using a traditional ceramic template or using the mathematics of isosceles triangles (Dufraisse 2006). The former is faster, but potentially more error prone; the latter is generally more accurate but takes longer. Both are subject to the vagaries of variability in wood growth. Results are usually grouped by diameter classes and used to show the use of “small,” “medium,” or “large” woods, with the goal of relating any changes to selection or cultural behaviors, environmental factors, or both.

Ancient charcoal production

The production of charcoal was, and is, a rural activity. Charcoal fuel will provide about 1.8 times the calorific potential of fresh wood and was the preferred fuel in cases where consistent temperature was required. Charcoal also burns with little or no smoke, and provides an even and “spit-free” heat. It is about one-third the weight of wood (by volume).

Wood charcoal fuel is made from a quantity of raw wood arranged in a stack (or pit). “Charcoalification” (as opposed to combustion) occurs in an oxygen-depleted atmosphere. Quantities of wood were usually cut to measure (about 1 m long), and the stack ignited (Veal 2012). Oxygen depletion

was achieved by covering the stack with soil or leaves and charcoal dust. Access to water was essential (to prevent full ignition of the stack). Charcoal making has been presumed to be an easy and almost spontaneous task, but the opposite is true. Care to cut wood (in fall or winter), then sort, stack, and dry it is required. Charring (usually in summer), requires a high level of technical skill, and this precludes economic quantities of charcoal being made without considerable planning, although charcoal can be made relatively easily in small quantities. It is probable that early humans discovered the utility of charcoal well before its use escalated in historical periods, although the matter has not been explored.

Observation of archaeological charcoals, together with ethnographic evidence, suggest that ancient charcoal fuel was made using different “recipes” depending on its intended use. Charcoal for domestic use can be made at the rate of 4–5 volumes of wood to produce 1 volume of charcoal (to produce a product that is about 65 percent carbon). This process retains some of the organic volatiles so that later combustion is facilitated. For industrial uses such as iron smelting a higher quality product (perhaps 80–85 percent carbon content) is required (Schenkel et al. 1998, 515), taking a minimum of 10–12 volumes of wood to make 1 volume of charcoal. This raises the question of how much charcoal as opposed to raw wood was consumed. Reflectance, a technique used in coal provenancing, relies on the observed “shininess” of a fractured charcoal being linearly related to its absolute burn temperature. It is currently being employed to try to resolve this question (Veal, O'Donnell, and McParland 2016).

In a big city, charcoal fuel may have been the preferred domestic fuel partly as it would have been cheaper to transport. The size of portable cooking hearths and the closed nature of heating braziers from Roman Pompeii suggest the use of charcoal as fuel rather than wood. Latin sources explicitly state that *carbone* was the fuel of choice in braziers.

Most processes requiring temperatures below about 800–900 °C (ceramic production) do not require the use of charcoal, whereas high temperature processes requiring a reducing atmosphere (above 1100–1200 °C), that is, iron smelting, do (Sim 2003). We cannot presume charcoal was not

used in lower temperature industrial processes, but common sense suggests it is less probable. A further consideration is the type of fire required. Slow, steady fires are best served by charcoal fuel. Technologies that required sudden temperature rises and falls are often best served by raw wood.

Economic modeling

Modeling may be carried out to assess the area of forest required to support the wood fuel supply for a city or settlement. The fuel supply to Pompeii over c. 400 years has been considered in detail (Veal 2012). The model addresses quantitatively a limited range of probable population sizes and possible fuel consumption levels in the city, taking into account relative consumption of charcoal and raw wood fuels, and forest productivity. Results are interpreted in light of the ecology of ancient southern Campania. This model could be applied more widely, providing population estimates may be gleaned, and climate and fuel used estimated.

SEE ALSO: Environmental Archaeology; Glass and Faience

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Companion Animals

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From the beginning of their existence, domestic animals of all kinds played major roles as food, in health, in techno-economic progress, beliefs and religion, social relationships and landscape shaping or management (see DOMESTICATION). Most of them, especially mammals, have woven ever closer relationships with humans. Some even became companion animals, because they lived at least part of their time inside dwellings as intimates of the household. Dogs and cats are the most common type of companion animal. There are roughly equal numbers of dogs and cats in the world today, numbering over a billion individuals, and as such they have major social and economic impacts. Therefore, deciphering the origins and long history of these animal's relationship with humans is almost as important as understanding the origins and history of our own species.

Where and when were dogs and cats first domesticated? How and why did they become companion animals? Have they always been pets? During the last 15 years, these important issues have stimulated intensive archaeological and zooarchaeological research (see ZOOARCHAEOLOGY), including the use of morphometrics and aDNA (see ZOOARCHAEOLOGY AND ANCIENT DNA), resulting in a wealth of new knowledge.

Dog, the domestic animal of hunters

It is clear from zooarchaeological investigations that the wolf (*Canis lupus*) is the unique ancestor of all dogs (*Canis familiaris*; Clutton-Brock 1999). This has been confirmed by the genetic analyses of modern wolves and dogs in conjunction with paleogenetic investigations (Larson et al. 2012).

The earliest evidence for dogs is mostly based on the discovery of *Canis* archaeological skeletal elements of much smaller size than those of smaller modern or ancient wolves. Such skeletal remains appear suddenly at numerous sites between 13,000 and 10,500 cal BC, in France, Switzerland and Germany, and in Spain, maybe as early as 15,000 cal BC. These western Europe Upper Paleolithic small dogs (WEUPSD) are associated with the Late Magdalenian, Azilian, or Laborian cultures (Pionnier et al. 2011). Two other areas in the Old World, north China and the Levant, have provided more or less contemporaneous evidence (ca. 10,500 cal BC) of the presence of small canids that are interpreted as domesticates. The discoveries are still rare in the former area, but in the latter, dog remains have been described from Late Natufian archaeological contexts from southwest Anatolia and the north Zagros to the south Levant, some of them in association with inhumations (Larson et al. 2012). At the Palestine site of Ain Mallaha, a young dog skeleton was found in one of the deceased's hands. In Germany and Russia, large Magdalenian canids, the same size as wolves but with a short snout and a broad palate, are also considered to be early domestic dogs.

For most zooarchaeologists, the occurrence of more or less contemporaneous early dogs in such distant areas pleads for several independent domestication events in Eurasia, anywhere within the wolf's very large distribution range. Contra to this, the first genetic investigation seemed to support an alternative hypothesis, a unique origin in China, followed by diffusion of domestic dogs across the rest of the world, including America and Australia. However parallel analyses of genetic diversity in African village dogs supports the multiple origin hypothesis. More recently, geneticists have established that genetic diversity in modern dogs mostly results from selective breeding from the nineteenth and twentieth centuries and that little or no information concerning the early history of dogs can be inferred from the genetic diversity of the modern populations, meaning that paleogenetic data are

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required to explore the origin and history of this species (Larson et al. 2012). There is clear evidence from the latest ancient DNA investigations that dogs were not domesticated in America, Africa, or Australia, but introduced to these continents as domesticates during the Upper Paleolithic. Recent investigations based on a large aDNA dataset has identified at least two domestication areas, in Europe and Asia respectively (Frantz et al. 2016). Further investigations may increase this number and reconcile molecular and morphological approaches. DNA next generation sequencing (see DNA: NEXT GENERATION SEQUENCING) has already provided information about the apparition of new coat colors and the evolution of the ability to digest starch in the domestic lineages (Ollivier et al. 2016).

It is not impossible that dogs were domesticated earlier in the Paleolithic and even possibly by Neanderthals. In Belgium, the Czech Republic, and Siberia, the discovery of large canids showing broad palates, tooth crowding, and skull proportions different from both modern wolves and dogs suggests that wolves could have been domesticated without any reduction in body size earlier than 30,000 BP. However, subsequent analyses have shown that all the particularities of these so-called early dogs can be accounted for in the much larger domain of variability of ancient and modern wolves (Boudadi-Maligne and Escarguel 2014).

Like Paleolithic human hunter-gatherers, wolves formed complex social groups and developed collective hunting strategies directed at the same middle or large sized prey. The two species fed on the same carcass or even preyed on one another. They used the same caves, with archaeologists finding the coprolites and gnawed bones resulting from wolves' meals, and the chipped stones and fire places left by humans in the same layer. In addition, wolves could have scavenged garbage from human occupation sites or people could have kept and bred cubs as pets. As competitors, collaborators or commensals, wolves weaved multiple ecological and symbolic relationships with humans over millennia across the whole of Eurasia. Ecological, ethological, and ethnological information suggests that domestication appeared as the consequence of one or several of these relationships, when humans began to deliberately accept and even favored the

presence of wolves within their groups. However, archaeology cannot yet tell us how and why this happened.

Neither do we know the role that dogs played in Paleolithic hunter-gatherer societies. Did they help with hunting and driving game, as suggested by some Mesolithic wall paintings in the Sahara or in Spain? Did they tow sleighs? Were they also used to alert people to the presence of other predators or people outside of the group? Did humans already appreciate them as "settlement cleaners?" Were they used for keeping people warm as recently in some Aboriginal societies, in Australia? Were they also pets? Butchery and cooking marks on bones indicate that wolves and dogs were consumed everywhere in the world throughout the Upper Paleolithic, and that their pelts were valued.

With the beginning of the Neolithic, diversity in the shape and size of dogs increased. In some regions at least, their status seems to have shifted from one of hunter to garbage scavenger and guard dog. As close companions of shepherds, they would have played a role in the protection of flocks against predators. However, their bones still appear in small quantities in human food refuse.

With the emergence of empires, in Africa (Egypt), Asia (Persian or Chinese early dynasties), Europe (Greek than Roman) and even America (Clutton-Brock 1999), both iconographic representations and skeletal remains indicate people selectively bred lineages of dogs, namely hounds, huge dogs and small "lap" dogs. However, these early selected lineages played only a minor role in the emergence of modern pedigree breeds which were developed starting afresh from mongrels. Parallel to this recent morphological and behavioral diversification, dogs were used for a wider variety of purposes, e.g., for herding flocks, for sport, and as guide dogs for the blind.

Cat, the domestic animal of cultivators

Zooarchaeological and genetics shows that the ancestor of all modern domestic cats (*Felis catus*) is a subspecies of the wild cat *Felis silvestris* ssp. *lybica*, that presently lives in North Africa and

Southwest Asia (Driscoll et al. 2009). Domestic cats have long been considered to have arisen in Egypt, where paintings indicate that they existed at least as early as twentieth–nineteenth centuries BC (Clutton-Brock 1999). However, skeletal evidence was lacking, because there is very little morphological difference between the bones of wild and domestic cats. Only in some special archaeological contexts can the presence of cat remains be used to suggest domestication, such as the hundreds of mummies deposited in sanctuaries devoted to the goddess Bastet. The recent discovery of such a special context in the Predynastic elite cemetery of Hierakonpolis (a grave containing one male and one female cat skeleton along with four kittens from two different litters) pushes the earliest evidence of cat domestication in ancient Egypt back to 3,800–3,600 cal BC (Naqada IC–IIB period, Van Neer et al. 2014).

Surprisingly, similar evidence has been uncovered in the late deposits of the Cyprus Pre-Pottery Neolithic (PPN) B site of Shillourokambos, dating to 7,500–7,000 cal BC. This revealed that the common history of cats and humans began much earlier in the Levant than in Egypt. A complete skeleton of a large young male cat was found in an inhumation carefully deposited facing the deceased (Driscoll et al. 2009). The association of these two individuals in the grave and consequently in the hereafter suggests strong spiritual links between at least some cats and humans by this early date. In addition, large-sized cat remains have been discovered in numerous early Neolithic archaeological sites in Cyprus contemporary with the first introduction of agriculture to this large Mediterranean island located 70 km off the Levantine coast. As there were no wild cats endemic to the island, there can be no doubt that people introduced cats to Cyprus as early as the Late PPNA, 9,000–8,600 cal BC.

Why did the earliest cultivators in the world undertake risky sea voyages together with cats, which were still very large, like the wild cats and potentially aggressive, although captive or tamed? It would seem that they were needed to control mice. Small mammal analyses show that commensal mice (*Mus musculus* ssp. *domesticus*) invaded the Levantine human settlements as soon as people started to accumulate cereals and legumes in the earliest sedentary Natoufian

hamlets. Zooarchaeological investigations also indicate that wild cats (and other small carnivores such as fox) became more abundant in the archaeological record starting from the PPNA, when the cultivation of wheat (see WHEAT) began (Vigne 2014).

Interestingly, a parallel but totally independent process has been recently described from the north China Neolithic. Remains of leopard cats (*Prionailurus bengalensis*), which were very frequent in this area, and which behaves the same way and occupies the same ecological niche as *F. s. lybica*, were frequently found in the Yellow River Neolithic villages. Some of them comprise skeletons deposited in graves. Some others show exceptional tooth wear suggesting extreme old age which is uncommon in the wild. All of these examples are slightly smaller than the wild form (Vigne et al. 2016). The leopard cat was therefore involved in an incipient domestication process. It seems that it was subsequently replaced by the western domestic cat descending from *F. s. lybica*, since all the domestic cats now present in China are genetically related to the latter.

Thus, in at least three different areas in the Old World, wild small felids were attracted by the proliferation of rodents resulting from early food storage and refuse accumulation. They became commensal and people are likely to have favored this natural process in order to control rodent pests or even because they wanted pets (Vigne 2014). Whether the Levantine or the Egyptian domestication gave birth to the modern domestic cat lineages is still unknown.

Contrary to dogs, small felids are naturally less variable because their morphology and behaviors are strongly constrained by their adaptation to the very specialized activity of hunting small mammals and birds. As this capability was the main reason why cats were domesticated, their morphology has remained largely unchanged since initial domestication. Diversity in form and shape dates principally from the start of the twentieth century when humans developed the pedigree breeds, including Bengal cats, which result from the hybridization between western domestic cats and wild Chinese leopard cats.

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Dairying

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The management of animals for dairy and the processing of dairy products are important industries in present-day societies and milk and its products make up a large component of the global diet. There are three main dairy species: sheep (*Ovis aries*), goat (*Capra hircus*), and cattle (*Bos taurus*). In Europe, cattle dominate dairy production particularly in northern countries, whereas across the Mediterranean basin and in the Balkan regions sheep and goat play important roles in providing milk and meat for pastoral communities. In addition, there are several other domesticated ungulates that are used as dairy animals across the world: the horse (*Equus caballus*, Central Asia), the donkey (*Equus asinus*, Africa), the one-humped dromedary camel (*Camelus dromedaries*, Middle East and Horn of Africa), the two-humped Bactrian camel (*C. bactrianus*, Central Asia), the yak (*Bos grunniens*, Himalayan Plateau), the water buffalo (*Bubalus bubalis*, South and Southeast Asia), and, to a lesser extent, the reindeer (*Rangifer tarandus*, Arctic Circle). These animals, together with the three main dairy species, are exploited for milk products that are transformed into different food staples. For example, horse milking has been practiced in central Asia since prehistory (3500 BC; Outram et al. 2009), and mare's milk is the basis of koumiss, a popular alcoholic drink, whereas yaks are concentrated mainly in the Tibetan plateau and produce rich milk, high in fat content, which is then made into butter, a food staple of the region.

Dairying provides a source of foodstuff that can be transformed into storable products that can act as a buffer for poor harvests and during periods in the annual season when food may be scarce. However, the ability to digest milk varies across populations. Lactose is the sugar within milk and, to digest this sugar, the body needs

to produce the enzyme lactase. The phenotype called lactose intolerance is in 65 percent of the global population; the remaining 35 percent have the phenotype called lactase persistence. The production of lactase is switched off in humans after they are weaned. However, in certain populations a mutation has occurred in the genetic code that allows for the production of this enzyme to persist. In Europe, the genetic mutation associated with lactase persistence is -13, 910T. The lowest frequency of this allele is in southeastern Europe; by contrast, the highest frequency is in northwestern Europe, where it reaches 95 percent (Itan et al. 2010). It has been proposed that there is a close relationship between the distribution of the allele and the development of dairy practices (Holden and Mace 1997).

The ejection of milk from the lumen to the teat cisterns is stimulated by the hormone oxytocin, which is important before and after parturition, for maternal behavior and bonding, and for milk ejection and letdown. Its production in the pituitary gland is stimulated by the sensory and tactile stimulus of the young, or through artificial means. Species vary in their ability to let down milk in the infant's absence; and phenotypic characteristics such as milk production are more plastic in some species than in others. For example, the letdown of traditional breeds of cattle is affected by the loss of the calf (see Figure 1). Therefore it has been proposed that early domesticated cattle would have required to be stimulated either by the physical presence of the calf or through artificial means, for instance by blowing into the cow's anus or vagina. Goats, on the other hand, are generally unaffected by the removal of the kid; and, to a lesser extent, sheep exhibit a similar behavior. The initial adoption of a particular dairy species would have been related to availability and to environmental tolerance or adaptability. Alongside other factors such as climate, cultural preferences may also have played a role in the development of husbandry practices and in the type of dairy products created.

The debate surrounding the evolution of European Neolithic dairying practices began

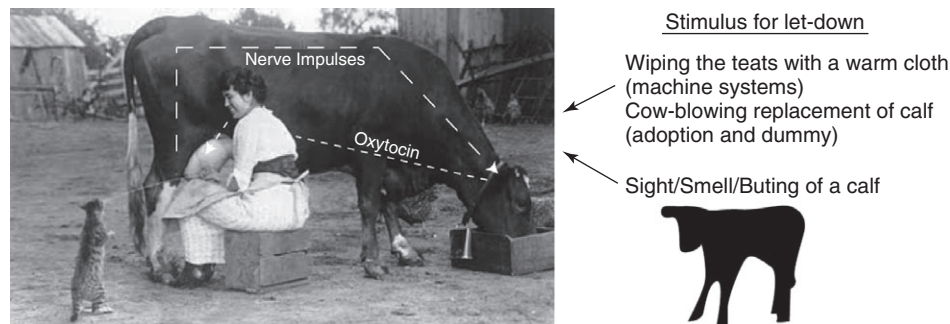


Figure 1 Stimulus for letdown graphic.

Photograph published courtesy of University Historic Photograph Collection, Colorado State University.

with the publication of Sherratt's (1981) theory of a "secondary products revolution," where "secondary products" refers to renewable products such as milk, wool, and labor. Sherratt's initial hypothesis was that dairying evolved alongside the Near Eastern early state societies of the fourth millennium BC, primarily for the reasons that early domesticates had poor letdown and human populations were lactose-intolerant. Advances in the organic residue analysis of ceramics (see *FOOD RESIDUE ANALYSIS*) have changed our understanding of the role of milk in early Neolithic cultures (Evershed et al. 2008). Large-scale analyses of ceramics from Neolithic contexts across Europe have shown that by the seventh millennium BC people were already processing and consuming milk (Debono Spiteri et al. 2016). In relation to lactose intolerance, the presence of dairy residues in pots indicates that processing techniques were employed to reduce the lactose content, as the sugar breaks down during cooking and fermenting.

Reconstructing dairy husbandry relies on the detection of the age and sex of animals in the zooarchaeological record (see *ZOOARCHAEOLOGY*). Sexing animal remains is hampered by butchery and taphonomic processes: these led to the destruction of whole elements needed for sexing, such as metapodials and pelvises. Ancient DNA has been used to sex elements and to deal with these data in conjunction with standard age-at-death analysis (see *ZOOARCHAEOLOGY AND ANCIENT DNA*). Animals' age at death can be determined from dental eruption, wear, and replacement and from postcranial fusion. The latter method provides large age

groups, and the results cannot be refined to allow the detection of subtle differences in slaughter practices associated with dairy husbandry. Thus, in general, zooarchaeologists use the age at death derived from the state of dental eruption, replacement, and wear. The frequencies from this analysis are presented mainly as triangular diagrams, survivorship curves, or histograms.

To interpret mortality profiles, models of subsistence dairy practices have been proposed on the basis of ethnographic observations (see Vigne and Helmer 2007). The development of models for interpreting mortality profiles is fraught with difficulties. Early domesticates are not comparable to modern breeds, which have been selectively bred for high milk yields. Furthermore, mixed subsistence practices would have been employed (rather than single-product systems). For example, Payne's (1973) initial models for milk, meat, and wool production for sheep have since been criticized for being unrealistic in relation to Neolithic husbandry practices, as they are based on those of Turkish market farmers. Further models of mixed husbandry practices have been proposed by Vigne and Helmer (2007) on the basis of ethnographic examples from subsistence farmers. For cattle, a postlactation slaughter model has been suggested, whereby calves are slaughtered after lactation, during weaning (Balasse and Tresset 2002). An intensive slaughter model for ancient dairying has also been proposed, whereby calves are slaughtered before the age of six months (Vigne and Helmer 2007). Milk letdown could have been maintained by artificial means and

through the sharing of calves. In marginal areas such as the Isles of Scotland, slaughtering one calf would have eased the pressure on fodder resources.

Along with mortality profiles, biomolecular analysis (see ZOOARCHAEOLOGY AND STABLE ISOTOPES) has aided our understanding of dairy practices. Measurements of $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ from collagen samples from the mandibular bone, where the dental eruption stage of the tooth adjacent to the bone sample is used as a time frame, can be employed to reconstruct the paleodietary history of cattle and thereby to provide an insight into weaning management practices. Values of $\delta^{18}\text{O}$ from incremental samples of enamel along the tooth axis can also be used to estimate the length of the birthing period (Balasse et al. 2012). Complementary stable isotopic analysis, in conjunction with mortality profiles, has been used to provide a detailed examination of herding practices during the Neolithic.

Recent pan-European projects (LeCHE FP7-ITN-215362-2; NeoMilk FP7-IDEAS-ERC/324202) have used multidisciplinary approaches to the understanding of the role of dairying in Neolithic societies and of how dairying has led to changes in human populations. At present, the picture that emerges is one of diversity. Ceramic vessels appear to have been used for processing dairy products from the beginning of pottery production as evident in the Sea of Marmara. This pattern varies for European Neolithic cultures, with strong evidence for dairying in western Mediterranean cultures such as Impressa and Cardial, but not in northern Greece. The correlation between high concentrations of milk lipids from pots around the Sea of Marmara and cattle, which dominate zooarchaeological assemblages, have led researchers to hypothesize that cattle played an important role in dairying. Early Neolithic cultures spread into central Europe, possibly following the riverine networks. Cattle played an important role in these communities, for example in the Linearbandkeramik culture. Therefore it has been proposed that dairying was an important food resource for these cultures. Analysis of ceramic sieves from the Polish site of Ludwinowo appears to confirm this hypothesis. The ongoing in-depth analysis of butchery practices and age at death, coupled with

organic residue analysis, indicates that the situation is more complex and fluid than previously believed. The production and consumption of dairy products would have been influenced by socioecological factors such as cultural tastes and the stocking capacity of a landscape for a herd of lactating animals. However, what is clear overall is that dairying was an important resource for Neolithic farmers and contributed to the expansion of Neolithic societies across Europe. Further research is needed to understand the evolution of dairying and dairy animals in other regions of the world.

SEE ALSO: Cattle

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Deep-Sea Fisheries

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Deep-sea fisheries, as currently defined by the Food and Agriculture Organization, operate at a depth ranging between 200 and 2,000 meters, “on continental slopes, oceanic seamounts, ridge systems banks” (Food and Agriculture Organization of the United Nations [FAO] 2010–18). Bottom-living and mid-water species are targeted through a range of gears such as “bottom and mid-water trawls, pots, and longlines” and the process “require[s] significant investment” (FAO 2010–18). However, when discussing deep-sea fisheries of the past, it is more relevant to describe them as offshore, as opposed to coastal or shore-line fishing (see FISH). Offshore fishing was, and continues to be, more risky than inshore fishing; especially in the age of sail, it was more exposed to changing weather conditions. The crews were far from their home port and vulnerable to disagreements over fishing rights. Fishermen also crossed open oceans, such as the Atlantic, to access distant fishing grounds and to bring the stored catch back to port at the end of the season.

This entry is written from a British and northern European viewpoint. The primary focus is on cod (*Gadus morhua* L.), the most commercial of the Gadidae, and on herring (*Clupea harengus* L.), a Clupeid. These two cold-water shoaling species have been the major targets of commercial fisheries from at least the late tenth century and until relatively recently. The history of both cod fisheries and herring fisheries demonstrates competitive fishing between nations, as demand grew with population growth and urbanization.

Many fish found in the deep sea are neither static nor restricted to that habitat. Migrations take place seasonally, for feeding and spawning. Fish often remain in discreet breeding groups and follow the same route each year. Immature individuals tend to be found closer

inshore and move into deeper waters as they grow—a process known as recruitment. These movements are closely monitored by fishermen who determine the balance of maximum return and profit against risk in the open sea. Before mechanization, dependence on wind and the lack of refrigeration were significant factors limiting the distance and time required to deliver fresh fish to shore. Steam-powered vessels and icing at sea were not introduced until the nineteenth century; freezing at sea was first practiced in the 1920s. The very success of modern factory fishing vessels, which catch, process, and freeze fish on board, spending months at sea, has contributed to the serious depletion of fish stocks and to the decline of traditional fisheries.

Cod has long been prized for its flesh and for its oil, the latter concentrated in the liver. “Train oil” was initially used for dressing leather, for lighting, and, later, as a medicinal source of vitamins A and D. Cod can grow to well over one meter in length, in a variety of habitats in the North Atlantic and the Arctic, up to depths of 600 meters, forming schools 30–80 meters above the seabed. They have a preferred temperature of around 6°, which can go up to a maximum of 15°. Young fish are found closer inshore, as are adults during the winter months, to the south of their range. Cod gather on banks in order to feed; these uprisings in the seabed create an area of shallower, nutrient-rich waters. There are a number of fishing banks in the North Atlantic, the largest being the Grand Banks off Newfoundland, where the cold Labrador Current meets the warm Gulf Stream.

Cod fisheries had long been important off the Norwegian coast: air-dried cod was made in the Lofoten Islands as early as in the Viking period. The North Sea, Iceland, and, by the late fifteenth century, the Newfoundland Grand Bank waters successively became the focus of European cod fisheries, whose fishermen went there for the season. Such was the value of these waters that fishing rights became fiercely contested and politicized.

Cod were initially caught using single hooked and baited hand lines. In the postmedieval

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period long lines were developed, each with many “snoods” (short lines with a baited hook) attached to the main line. Setting and hauling in long lines was very labor-intensive and not mechanized until the 1960s. In the nineteenth century the development of trawls maximized the return on cod catches. This accelerated overfishing, which had already impacted on what was often seen as a limitless supply. However, there were concerns, as indicated by the early legislation that protected freshwater fish populations and immature marine stocks.

The traditional “dogger,” an open rowing boat with sails used at least from the fourteenth century, was robust enough for the North Sea and Iceland seasons. For Newfoundland, bigger vessels were required, which carried larger crews and supplies across the Atlantic. Initially Breton and Basque fishermen made the journey; later on they were followed by other nations, the English joining relatively late. The fishery was the subject of much dispute and rivalry. These fisheries were not of the deepwater variety, as cod were caught in comparatively shallow waters, but fishermen crossed the Atlantic to reach them.

Cod bones are relatively uncommon in archaeological deposits before the tenth century AD, when the commercialization of the fishery took place, to meet the new demand from growing settlements (Barrett, Locker, and Roberts 2004). Large cod were found in some earlier Saxon monastic and “wic” (trading towns) contexts in the southeast of England and are thought to reflect high status.

Herring is a member of the Clupeidae, found north of 30° latitude, in both saline and brackish conditions. Tolerant of water temperatures up to 18° but preferring 8°, herring can be found at depths up to 364 m. They spawn over winter in shallow waters, but as adults they feed offshore. Averaging 30 cm in total length, they can be found in numbers of up to a billion in one single school (Lamichhaney et al. 2012). Discrete breeding groups have a specific annual migration route to their spawning grounds and can be distinguished by variations—for example, in the numbers of vertebrae (Hodgson 1957, 15) or in the size of the fish—and also by genome (Lamichhaney et al. 2012). In the North Sea there are three main groups: the Buchan, the Dogger, and the Downs groups. Buchan herring, the most

northerly, migrate first, then Dogger, and lastly Downs; this ensures that, although their routes overlap in part, they do not mix. At times herring are close inshore and young fish enter estuaries, being netted in large numbers by local fisheries and become increasingly common in archaeological deposits at larger settlements from the Roman period onward. The commercialization of the fishery is evident from the late tenth century AD: herring bones are often the most numerous specimens identified by species in archaeological deposits from this period (see FISH; Barrett, Locker, and Roberts 2004).

The history of the herring fisheries was as politically charged as that of cod fisheries and was vulnerable to boom and bust, as fish numbers fluctuated. These oily fish soon became rancid and, prior to refrigeration, much of the catch was cured. In Britain, the North Sea fisheries were centered around East Anglian ports, where fresh, salted, and pickled fish were an important trade, hard-smoked “reds” being produced from the fourteenth century. The Dutch were soon dominant in the fishery and nations competed at developing new curing methods in order to capture this lucrative market.

Herring are netted with seines and gill nets; originally this operation was conducted from small open rowing boats, but, as the industry grew, the boats and the crews became larger. The shallow-bottomed boats were used in inshore waters by the Dutch to land their catch in drift nets. These were superseded by Dutch “busses,” an early factory ship that soon dominated the North Sea herring industry.

The archaeological evidence for these fisheries consists primarily in the bones recovered during excavation (see ZOOARCHAEOLOGY). Fishhooks and weights have also been found but are difficult to attribute to specific fisheries. The location and contextual date of fish bones show growth in the market that delivered cod and herring through time and space. Quantitative methods suggest when and where cod overtook herring as the prime commercial species.

Analyses of anatomical distributions have revealed “bone signatures.” The disproportionate representation of different parts of the skeleton can indicate whether cod bones were from fresh or from stored fish, as certain elements are

removed through salting and drying. Bone measurements can determine the size of individual cod; a particular range was considered best for storage (Barrett, Nicholson, and Ceron-Carrasco 1999; Hamilton-Dyer 1995). Even in a small fish like herring, processing methods can be observed from bone distributions. A specific gutting method was observed in a deposit in Denmark with bones predominantly from the throat area (Enghoff 1996).

The analyses of isotopic elements from individual cod bones recovered through excavation have been used to indicate the origin of these bones (see ZOOARCHAEOLOGY AND STABLE ISOTOPES). Stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) have a signature, determined by environmental factors attributable to a region (Barrett et al. 2008). The results reflect the expansion of cod fisheries designed to supply the market from the North Sea, the Baltic, Iceland, and ultimately Newfoundland.

Although much on the development of fisheries can be ascertained from documentary data, the zooarchaeological bone evidence has proved to be a crucial part of ongoing multidisciplinary projects that engage fish scientists and historians. The archaeological bone evidence has added new data for periods predating the collection of fisheries statistics; previously these statistics were used as a baseline in determining overfishing. The inclusion of bone data and of other evidence—such as early testimonies on bottom trawling before the first statistics taken in 1886 in the United Kingdom (Thurstan, Hawkins, and Roberts 2013)—has shown that overfishing was a problem well before these records began.

On-site sampling and sieving of deposits secures the recovery of the smallest fish bones (see SAMPLING IN ENVIRONMENTAL STUDIES). These have provided a database for meta-analyses of large groups of data that show trends in fish consumption, and therefore in fishing. The application of genetic and isotopic analytical techniques on cod bones in particular is a developing field and an important element in refining the history of fish stocks, in fisheries science, and in the development of proto deepwater fisheries.

SEE ALSO: Urban Environments;
Zooarchaeology and Ancient DNA

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Desert Environments

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The word “desert” comes from the Latin verb *deserere*—to abandon—so *desertum* means “abandoned.” In its very etymology, this word thus contains the notion of the temporal process that produced it: in other words, a desert is a place that was once inhabited. For this reason, desert environments play a fundamental role in the archaeological sciences as privileged locations for analysing the interface(s) between climate, landscape, resources, and humans.

Research on desert areas is particularly important when we consider the process of desertification, of enormous significance in the contemporary world. Desertification, that is the spread of deserts encroaching on more vegetation-rich lands, is triggered by both natural and anthropic factors. Today the study of past desertification can provide significant insights of help in combatting this process, which seriously affects large parts of the planet, including the use of traditional systems for managing land, water, and resources. There is no “official” definition of the term desert, so we refer here to landscapes currently characterized by scarce rainfall (under 250 mm per year according to Köppen’s 1918 climate classification), high temperature oscillations and sparse (or no) plant cover. This harsh climate type affects substantial areas of the planet (roughly a fifth of the earth’s land surface). The Arctic and Antarctic Polar Deserts are the largest cold deserts on Earth, whereas hot deserts are mostly located at lower latitudes. Desert environments are present in all continents, with different locational and physiographical features that may greatly influence the human presence. Despite their harsh environment, deserts are home to an astonishing biological and cultural diversity. Today, over one billion people live in deserts, mostly concentrated in towns and villages with vast areas where humans are virtually absent.

The Sahara, with a surface area of over 9 million km² (3.5 million square miles)—approximately a third of Africa—is the world’s largest hot desert. Located in the northern part of the continent, the Sahara presents highly diverse geographical, geological, and physiographical features. Stretching from the tropics in the south to the Mediterranean Sea in the north, and from the Atlantic in the west to the Red Sea in the east, it can be considered with some caveats a valid representative of desert environments. Although the iconic image of the Sahara Desert is that of large dune fields (*erg*, or *edeyen* in Arabic), it mostly consists of a flat, barren pavement covered with small rocks and pebbles, locally known as *reg* or *serir*. Except for the Nile, there are no permanent water courses. Former river systems (see RIVER SYSTEMS), now extinct or seasonally reactivated by occasional rains, are known as *wadis* and in several cases host large oases. A long tradition of environmental, archaeological, and rock art research beginning in the mid-nineteenth century has made the Sahara particularly rich in scientific data.

Given the scarce human presence, mostly restricted to oases and modern villages, anthropic pressures on desert environments in historical times—except for development and infrastructure projects—have been much less aggressive than in other biomes. This has helped, at least in part, to better preserve the archaeological landscape. Archaeological survey—by foot, camel, 4X4 vehicles and now drone-assisted flight recording—is a key method for identifying evidence of a past human presence (see FIELD SURVEY). Although this evidence varies from isolated scatters of stone tools to the remains of underground water channels, much scientific research in the Sahara has consisted of large-scale, extensive surveys (Kuper and Kröpelin 2006), with excavation being far more limited (Wendorf and Schild 2001).

More recently, the combination of remote sensing analysis of satellite imagery and the use of digital devices in the field has improved our ability to identify, map, and record archaeological sites in

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arid lands. Given the nature of the terrain and the peculiar physiography of desert landscapes where vegetation is virtually absent, we can distinguish between different types of locational context, each with a specific capacity to attract a human presence and preserve the archaeological record, and with its own degree of archaeological visibility.

Open-air contexts mainly consist of scatters of archaeological materials (lithics, pottery, bones, grinding equipment, etc.) and remains of stone structures (fireplaces, huts, walls, ritual/funerary structures, geoglyphs, etc.). Their state of preservation varies dramatically, as does their archaeological visibility. In some cases, erosional processes in desert environments create stone-line features consisting of an accumulation of dismantled archaeological layers, of extremely high density. Here, statistical methods of spatial analysis and sampling may greatly enhance our understanding of past human occupation(s). From a stratigraphic point of view, negative features normally prevail over positive ones and multilayered, stratified contexts are rare. Among the exceptional examples of good preservation, are the Early to Middle Holocene cemetery of Gobero, Niger, and some sites around Nabta Playa in Egypt. Both, however, are characterized by the presence of lacustrine sediments covering and partially protecting the archaeological features. Stone structures, particularly those with a funerary/ritual purpose, are of crucial importance for the study of Holocene populations, especially after the onset of desert conditions around 5,900 years ago (Tierney and deMenocal 2013). Sometimes these stone covers are the only protection against wind erosion, a major geomorphological agent in desert environments. For this reason, much archaeological research in the Sahara has focused on stone monuments, giving rise to an important tradition of studying ritual customs, funerary practices, and bioarchaeology (see BIOARCHAEOLOGY). Rock art sites (mostly graffiti and engravings on isolated boulders, cliffs, and rock walls) are another important segment of the desert's archaeological landscape. Their preservation is greatly endangered, not only by environmental pressures but also by a variety of anthropic threats.

Sheltered contexts, like caves, rock shelters, niches, and alcoves (see CAVES AND FISSURES), have been intensively used by human groups and

are still frequented by nomadic herders across the Sahara such as the Tuareg and Tebou. Their archaeological visibility is excellent on the ground making them easy to target during field surveys but much less so through remote sensing. Given their natural protection from wind, rainfall, and sunlight, the preservation of archaeological deposits is better than in open-air contexts, with some extraordinary instances from different parts of the Sahara. Arid conditions prevented bacterial activity, significantly favouring the preservation of organic remains, including fruits, seeds, and other plant macroremains. Pollen analysis (see PALYNOLOGY) and archaeobotanical studies (see PALEOETHNOBOTANY) can therefore be used to enhance our understanding of past climate and environmental variations in these landscapes, as well as the human exploitation of plants for food and fodder. Additionally, the repeated use of these places has created true palimpsests with complex stratigraphic sequences, as is evident in the central Sahara (Biagetti and di Lernia 2013). In these contexts, dung represents a specific type of archaeological deposit with extraordinary potential for defining and understanding ancient herding strategies (see COPROLITES). Shelters help to preserve artworks such as pictograms, engravings, and other markings. Caves and shelters may also preserve human burials—normally of the Holocene period—with exceptional instances such as the naturally desiccated bodies of several humans found in different parts of the Sahara including Ti-n-Hanakaten (Algeria), and Uan Muhuggiag and Takarkori (Libya).

The differing state of preservation of these diverse contexts may affect our capacity to date the principal environmental and cultural phenomena correctly. This is particularly important for research on the timing and dynamics of desert formation, and the adaptive mechanisms developed by past human groups. Climate studies have a privileged position in desert environments, which should be considered true laboratories for analysing the relationship between humans and the environment. Significant advances in the field of climate change and climate modeling have been made thanks to research in the Sahara, in particular its central and eastern regions. Geomorphological studies of ancient lacustrine sediments and palaeo-shores, and core drillings of surviving lakes, have greatly expanded our

knowledge of the Pleistocene and Holocene climate variations (Kuper and Kröpelin 2006; Drake et al. 2011), providing crucial information for defining the so-called “African Humid Period.”

OSL, TL, and radiocarbon datings are routinely used to date ancient landforms, archaeological contexts, and rock art sites (see DATING IN ARCHAEOLOGY). A particular tool is the patina known as “desert varnish,” usually a dark coating consisting of different minerals and manganese covering open-air rock forms, sometimes including rock-art panels and stone features. Its chemical composition, color, and inner microstratigraphy may provide a wealth of information on past environmental variations. Furthermore, the organic particles trapped in the coating can be AMS radiocarbon dated, providing a *terminus ante quem* for the object investigated. Studies of desert varnish are common worldwide, with significant traditions in North America and the Sahara (Dorn 2007).

In desert environments, oases are crucial hotspots for plant and animal life, including humans. In the Sahara, the oases formed in the Late Holocene and hosted the first sedentary communities. In these areas, the archaeological record may consist of villages, hamlets, and towns. Monumental tombs and infrastructure—such as *fogārah* (underground water capture systems)—also punctuate specific segments of the landscape (slopes, wadis, etc.). Although oasis formation is a natural process, its maintenance and development is due to the human intellect and their painstaking efforts. The exploitation of water and the capacity to cultivate these regions are evidence of the extraordinary human ability to adapt to harsh environments. In preindustrial times and sometimes even today the only access to water consists of rock cavities filled by occasional rainfall. Called *gueltas* in Arabic, these features are of the utmost importance for nomads now living in the desert, and the same was true in the past. Many *gueltas* are historiated by artworks, engravings, rock markings, and inscriptions, sometimes thousands of years old.

By definition, food resources in desert environments are scarce and unevenly distributed. Seasonal gathering is restricted to a few watered areas, such as the *gueltas* of protected wadi systems. Cultivation is limited to the oases, where cereals and other pulses are grown thanks to

springs and wells. Traditional wells (*bir* in Arabic) normally exploit very low water tables, whereas deep wells (mechanically built with electric or motor pumps) may use fossil water and thus favor industrial-type production. Flood-recession cultivation is a traditional form of farming using temporary ponds, known in the Sahara as *etaghas*, *tesahaq*, or *tmed*. The geomorphological features of these ponds allow for occasional cultivation after heavy rainfall: their flat surfaces and more limited exposure to wind and sun mean that they retain water for longer. Research in the central Sahara suggests that this traditional farming method may date back at least to pre-Islamic times. Archaeological evidence around these ponds consists of small campsites, farming facilities (walls, ditches, fences, stone markers), a few artifacts (potsherds, grinding stones, and lithic tools) and rock-art markings.

Given the decline in wild fauna, hunting is currently little practiced although poaching unfortunately still occurs. Herding is the best form of subsistence adaptation to desert environments, especially when practiced on a year-round nomadic scale that prevents overgrazing and the deterioration of pasture and water resources. In Africa, and in the Sahara in particular, pastoralism is a very ancient form of subsistence, dating back to the Early Holocene and preceding agriculture by thousands of years (Marshall and Hildebrand 2002). The archaeological reconstruction of herding is based on the study of settlement organization, investigation of faunal remains (see ZOOARCHAEOLOGY), identification of milking through pottery residues, analysis of coprolites and spherulites, and the recording and interpretation of artworks. The combination of archaeological data and spatial analysis of settlements is of the utmost importance. Ethnographic evidence and ethnoarchaeological analysis can greatly improve our capacity to reconstruct past pastoral systems.

Given their natural constraints, large areas of desert environments are barely populated. Yet various human groups chose, or were forced to choose, these places for maintaining their traditional lifestyles. This is true of the nomadic herders of the Sahara, but also for example of the San hunter-gatherers of the Kalahari in southern Africa or the Aborigines of Australia's desert outback. The ethnoarchaeological study of these groups is crucial for understanding

the mechanisms of adaptation(s) to these harsh environments. Since the 1950s, such studies have been fundamental for theory building and contributed significantly to the emergence of processual and, later, post-processual archaeology (David and Kramer 2001).

Despite the physiographic and environmental limitations, deserts have hosted great ancient societies. In the Sahara we have not only the extraordinary case of Ancient Egypt (although the presence of the Nile significantly influenced the environmental context), but also the emergence of the Garamantian state in the very heart of the desert. The mechanisms of settlement coagulation and political control in such environments have been thoroughly investigated by different teams bringing a different, and fresher, perspective to the theoretical debate on state formation and development (Mattingly et al. 2006).

The natural and cultural heritage of desert environments is seriously endangered (see HERITAGE AND LANDSCAPES). Environmental threats mostly result from the very nature of these regions: high temperatures, strong temperature oscillations, wind erosion. Anthropogenic threats are also very serious. Infrastructure building, underground exploitation, development, poaching, illicit trafficking, agricultural reclamations, and tourism are just some of the pressures that humans exert on this incredibly fragile heritage. Unlike wind erosion and thermoclastism, however, these threats can be mitigated. Plans for conservation and raising awareness of the need to preserve these environments are among the main aims of United Nations organizations and numerous NGOs, and also involve the local communities, the guardians of these extraordinary regions (Goudie and Seely 2011).

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Diatoms

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Diatoms are a very diverse and distinctive group of single-celled algae that are abundant in aquatic habitats. The silica valves enclosing diatom cells are taxon specific and are commonly preserved in aquatic sediments. These features, along with the sensitivity of diatoms to many aspects of water quality, led to their value in archaeological investigations.

An early application of diatom analysis to archaeological questions was during the 1940s in studies of prehistoric settlement along the changing shorelines of the Baltic Sea. The sensitivity of diatoms to salinity and the preservation of diatom sequences in the sediments of lakes isolated from the sea enabled the reconstruction of former sea levels and the prediction of former settlement locations through different phases of isostatic land uplift and eustatic sea-level change (see SEA-LEVEL CHANGE).

Diatom-based environmental reconstruction in coastal and estuarine archaeology is an important part of multiproxy paleoenvironmental studies (Sidell et al. 2000). In tidal habitats it is important to take account of autochthonous and allochthonous components of the diatom assemblages. It has become more common to use multivariate techniques to calibrate modern diatom communities with contemporary water chemistry and apply such models to fossil diatom assemblages in sediments of archaeological interest. For example, this has allowed the relationship of historic and prehistoric sites in London to be related to the changing nature of the River Thames. Other archaeological studies involving diatom analysis have shown the effects of both salinity change and anthropogenic nutrient enrichment (see WATER POLLUTION), for example in the fortified Roman town of Leiden in the Netherlands (Brandenburgh and de Bruin 2016)

and in the recent past in the vicinity of whaling settlements in the Arctic (Douglas et al. 2004).

The presence of diatoms in both contemporary and fossil clay sediments used in the manufacture of artifacts has led to the application of diatom analysis in studies of clay provenance and typology. These studies are exemplified by work on ceramics particularly of ancient material, where firing temperatures were low enough to allow the survival of diatom silica. In addition, investigations of diatomaceous clay bricks used in construction in ancient Egypt have been used to characterize the mud bricks (see ADOBE) and potentially to correlate bricks within and between monuments (Flower 2006). There have also been attempts to investigate past river water quality and clay provenance in the Middle East through the identification of diatoms preserved in dated clay tablets on which agricultural inventories were recorded in cuneiform script.

The presence of diatoms within internal organs can be used in the diagnosis of drowning. This diatom test for drowning, usually applied to assist pathologists in forensic investigations, has been employed at a Late Neolithic site in Sweden. Diatoms extracted from within human long bones were found to be similar to the diatom assemblages of sediment in a well. In combination with other archaeological evidence, this led to the suggestion of ritual killing (Carlie et al. 2014). Diatom analysis has also been applied to the investigation of the source of materials associated with ancient burials.

Diatom analysis is commonly used in the study of ancient boats. Both inland and seagoing vessels from the Bronze Age to the Medieval have been subject to diatom analysis. These studies have involved examination of the context of the boats, and sediments on which they came to rest. In addition, boat planks, caulking material such as moss, and other artifacts associated with submerged wrecks have been investigated by diatom analysis to assist in determining the range of environments in which the boats were used. The aquatic environments of several waterfront and harbor sites in northern

Europe and in the Mediterranean have also been investigated through diatom analysis, often in conjunction with foraminifera analysis (see FORAMINIFERA).

The use of geological diatom deposits with a high diatom content, deposits known as diatomite, provide a means of tracing the exploitation and trading of materials. Diatomite may have been deliberately used in manufacture or may contaminate artifacts.

Archaeological features such as cave sediments, wells, pits, post holes, and sediments around fish traps have been analyzed for diatoms to investigate local environments. Diatom analysis has been used in experimental archaeology to assist soil micromorphological interpretation of habitation floor layers where the drinking habits of livestock can be examined through the excretion deposits of diatom valves (see MICROMORPHOLOGY).

Diatom analysis of settlements built next to lakes, rivers, and channels has been used in multiproxy investigations particularly in northwest Europe. Examples of these settlements are the humanly constructed islands known as crannogs that supported buildings constructed in lakes and in sea lochs. The majority of crannogs constructed in Scotland, for example, date from approximately 800 BCE to 200 CE, although crannogs there and elsewhere exist from outside this age range. In the vicinity of these, other lake and riverside structures, and also moats and fishponds associated with medieval buildings, diatoms have shown evidence for eutrophication and aquatic habitat changes (e.g., Keevill 2004). These can be attributed to the nutrient inputs from the settlements and associated agriculture. At other sites, using diatom analysis, the freshwater nature of the settlement environment has been established following phases of marine regression.

SEE ALSO: Caves and Fissures; Lake Deposits; Paleoenvironmental Reconstruction

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Disaster Archaeology

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Scholars and the general public have long been fascinated by ancient disasters. Disasters have played major roles in human history, beginning with volcanoes affecting our ancestors in East Africa 3.6 million years ago (Oppenheimer 2011). The interest in nature's extreme events, such as volcanic eruptions (see ARCHAEOLOGICAL VOLCANOLOGY), earthquakes (see ARCHAEOSEISMOLOGY), droughts, and floods (see FLOODING), lies in their ability to produce an array of dramatic responses, including the collapse of societies or cities, of which the destruction of Pompeii by Vesuvius is the best known case. However, much of the literature on disasters is unilinear: A impacts B, disaster strikes, and the society suffers. This cause and effect paradigm emphasizes those most drastically affected. This directed emphasis is exemplified by the media, where the focus is always on the loci of greatest destruction for present day disasters, then quickly moving onto other topics, leaving long-term recovery and adjustments virtually untouched. Scholarship similarly has emphasized the immediacy of impacts. Only recently have archaeologists considered long-term recovery processes within social contexts (Torrence and Grattan 2002).

The study of disasters, perception of risk, and mitigation, have been dominated by the natural sciences and engineering (Riede 2015). The term "natural disaster" is an unfortunate reflection of that domination. However, there is a growing realization that social processes are fundamental components of disasters. Therefore understanding the cultural and social factors are at least as important as the natural forcing mechanisms. Just as a disease reveals to the physician the workings of the body, so to the social scientist the disaster reveals the working of the affected society. Recent decades have witnessed the emergence of social science studies of these topics.

While social scientists focus on the immediacies of risk, vulnerability, and mitigation of societies today, almost entirely in developed countries, anthropologists and archaeologists study disasters and their components around the world and over long timespans. The realization that the historical contexts that precede and follow a disaster are necessary for understanding an event has uniquely qualified archaeologists to study the long-term recoveries and adjustments made by societies. Further, archaeologists study the full range of societies, from hunting and gathering and horticultural egalitarian groups through chiefdoms and into stratified states and empires, providing a more comprehensive approach. By investigating societies prior to the disaster, the impacts of the event, and the long-term aftermath, scholars are discovering the complex ways in which vulnerabilities are produced.

The natural forcing mechanisms vary considerably around the world, summarized by Mauch and Pfister (2009). They include floods, droughts, summer frosts killing crops, earthquakes, volcanoes, famines, diseases, forest fires, and storms. A human universal is the need to explain the workings of their environment, and extreme events are regularly seen by traditional societies as sent by the supernatural domain, often interpreted as a result of human misbehavior (Krajick 2005). The cases examined often included progressive learning embedded in disaster responses, as societies that have learned how to ameliorate the negative impacts of future events. Traditional societies often embed quite rational behavior into their oral histories or religions, thus mitigating the impact of the next disaster. Native American societies along the Pacific Northwest Coast knew that the clash of the Whale sea deity with the Thunderbird sky deity creates an earthquake and perhaps a tsunami, so they mitigated risk by heading inland. Current residents of Seattle are less prepared for the next tsunami than were Native Americans. After the huge 2004 earthquake in Southeast Asia, the traditional Moken people perceived the ocean receding from their fishing villages, so they headed out to sea, and

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the tsunami wave passed under them with no difficulty. Over a quarter million more “modern” people living in coastal areas, but devoid of the traditional knowledge, were killed when the tsunami crashed into their shores.

Many disasters were interpreted as divine retribution for human misbehavior. When the Maya skybearer deities perceived significant human misbehavior, they stomped their feet, creating an earthquake, and then religious specialists interpreted the event and acted to change human behavior. In other cases, elites and royals claimed enhanced connectivity with the supernatural domain and thus had primary responsibility for the functioning of society. When functioning fails under a disaster, confidence can be lost and as a result religious-political upheaval or revolt can ensue, as exemplified by the Chinese emperor losing the mandate of heaven in the wake of a particularly severe drought in the mid-sixth century (Gunn 2000).

Societies that have faced recurrent disasters often develop cultures of coping, which can involve quite rational behavior, along with religious belief and psychological adjustment. Although their explanations differ fundamentally from our scientific explanations, societies affected by great geophysical stresses can learn from them, embed the knowledge in oral history and religious belief, encode emergency behavior, and thus provide resilience to future events.

Archaeologists have recorded different volcanic impacts on a wide range of societies around the world (see *ARCHAEOLOGICAL VOLCANOLOGY*). In spite of all the variability, comparative analyses are discovering some common patterns (Sheets 2001). Although it may seem counter-intuitive, “simpler” egalitarian societies often fared better than more complex societies when impacted by explosive eruptions depositing thick layers of volcanic ash across their landscapes. For instance, horticulturalists in the Arenal area of Costa Rica were impacted by 10 big eruptions of the Arenal Volcano in the past 4,000 years. The villagers fled to viable refuge areas, waited for a decade or two for ecologic recovery, and then resettled their original villages. The key factors in their resilience were small villages (a hundred people or less), low regional population densities, lack of warfare, available refuge areas, and food from domesticated plants and the biodiversity of

the tropical rainforest. Their recoveries probably were aided by oral histories. A different aspect of these villagers is presented toward the end of this entry.

The chiefdoms in nearby ancient Panama were similar to the Arenal villagers in many ways, but their social differences resulted in greater vulnerability to volcanic stresses (Sheets 2001). The chiefdoms engaged in capture warfare, and the landscape was more densely populated to provide more warriors. Each chiefdom had one or two thousand people. Although they functioned well for many centuries, they were on the threshold of sustainability. When the nearby Baru volcano erupted with a moderate-size explosion, people had to relocate and never returned. Although the eruption was smaller than all 10 of Arenal’s eruptions, the Panamanian chiefdoms had less resilience to the unanticipated stress and had no nearby refuge area because of warfare. They were therefore more vulnerable and the chiefdoms collapsed.

The state level societies of Mesoamerica, with their greater population densities and accentuated social differentiations among classes far greater than chiefdoms, were often highly vulnerable to natural stresses. For instance, Teotihuacan was the greatest city of Mesoamerica in the first half of the first millennium AD, powerfully influencing surrounding societies for hundreds of miles by their extensive trade network and compelling religion (Oppenheimer 2011). Over 100,000 people lived in this highland city, at some 7,000 ft in elevation, and thus close to the frost line. The climate was semiarid, so in years with average temperatures and rainfall on the corn, beans, and squash triad of crops grown would provide food for all. A bad year due to drought or frost could be tolerated by storage and exchange; however, their resiliency was greatly exceeded by the decadal-long drought and frosts that began in AD 536. In the years following the commoners rebelled against the elites, selectively burning elite temples and compounds as well as smashing the sculptures of the water deity, culminating in collapse.

The cause of this particular stress was unknown until recently. The cataclysmic eruption of Ilopango volcano, El Salvador, in AD 539 was the major player in causing a worldwide cooling and drought that lasted for over a decade (Oppenheimer 2011). Teotihuacan suffered the

distal effects of the eruption, as did so many other societies inhabiting marginally productive areas. The Maya living within a 100 mile radius of the volcano suffered the proximal effects: all people, animals, plants, fish, and other living things were completely eliminated in what is now El Salvador, and into adjoining countries. This was a complete cultural-natural disaster, as there were no survivors to initiate recovery, and the people who eventually recolonized the area were quite different.

Other volcanic eruptions in Mexico and Central America, as well as other parts of the world (Oppenheimer 2011) have caused varying degrees of stress on societies, and many of them recovered and often found new ways of coping with volcanic hazards. An example is provided by the villagers near Arenal volcano (Sheets 2001), where multiple eruptions affected small horticultural villages in the tropical rainforest. From about 500 BC to AD 600 individual villages acting independently abandoned their settlements and took refuge until ecologic recovery occurred. The villagers reestablished residence in their original villages and resumed single-file pilgrimages to their cemeteries, often located at considerable distances. At about AD 600 they established a shared cemetery, and it was shared by at least one village eastward toward the volcano, and at least one village westward on the dry Pacific drainage. Villages were much too small to have been endogamous, so marriages must have occurred outside of each village. The alliances and intermarriages that must have occurred formed relationships that could be used for refuge by the volcanic-impacted villagers. And when drought affected the western villagers, they could take refuge in the wetter tropical rainforest near the volcano, with its great biodiversity and biomass of edible foods. Eruptions were of such frequency, averaging one big one every four centuries, and many smaller ones, that villagers must have maintained an oral history of precursors, eruptions, and mitigating behaviors. Establishing a shared cemetery and the alliances that ensued provided refuge for the villagers struck by the eruptions, and provided food for the easterners when drought struck. This appears to have been a sophisticated example of risk management. Unfortunately, European-introduced diseases completely depopulated native villagers

in the area, with the Spanish Conquest, thus eliminating whatever oral history and traditional environmental knowledge had been achieved. When modern Costa Ricans settled the area in the twentieth century they were unaware of the hazard, did not know how to act when the precursors of the 1968 eruption occurred, and many perished. Mauch and Pfister (2009) cite other cases where colonization or modernization decreased resilience to disasters.

Natural and cultural components of extreme events have been, and continue to be inextricably intertwined, and they can take place over a long time. Only by incorporating the histories that precede and follow the manifestation of an event as well as the differential way that these events can impact society, can we begin to reconstruct past disasters. Disasters are now being studied by many archaeologists, often in large multidisciplinary research programs. And as a result, our understanding of vulnerability, resilience, and recovery are becoming much more nuanced.

SEE ALSO: Tephra and Volcanic Ash Analysis

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Domestication

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Domestication, like many other terms that have apparently straightforward meanings, is actually very hard to define. Within archaeology, meanings commonly range from socially oriented perspectives that emphasize domesticatory relationships of people with animals, plants, and places, to biologically oriented definitions that focus on the phenotypic and genotypic transformations in animals and plants as a result of human selection. There are also common misconceptions regarding domesticates, such as the requirement for human intervention in order for them to reproduce; such a definition would apply to only a handful of species in human history, most notably maize (*Zea mays*).

Taken at its most general, social domestication refers to the way in which things and places are brought into the human realm. Here there is no clear-cut demarcation of when domestication started because the processes involved are gradational, nonlinear, and multilayered. Effectively, domestication results from the intersection of a range of practices through which people intervene in the life cycle of animals and plants, as well as in the construction of place (principally at the landscape-scale). Further, the domestication of individual species is often entwined with “domestication” of the environment. Although proponents of more socially oriented definitions of domestication may lean on post-processual discourses, they often retain a teleological component; namely, the scale, directionality, and intensity of domesticatory relationships ratchet up through time.

For archaeologists, the domestication of animals and plants has primarily been empirically documented from morphological transformations in zooarchaeological (see ZOOARCHAEOLOGY) and archaeobotanical (see PALEOETHNOBOTANY) remains through time. As such, the archaeology of

domestication has been reliant on documenting phenotypic traits that are considered to characterize early stages in the domestication process and subsequent varietal differentiation. Using archaeobotanical and zooarchaeological methods alone, it was possible to document morphologically expressed phenotypic traits, such as nonshattering seeds and size reduction in animals, as opposed to behavioral traits that could not be directly observed in archaeologically preserved materials, such as photoperiod sensitivity in plants and sociality in animals. However, some morphological traits may not ordinarily preserve at archaeological sites—such as coat color and eye color in animals. In recent decades, aDNA has been used to identify population affinities and the emergence of genetic markers of specific traits associated with domestication, including a range of morphological and behavioral traits.

Two evolutionary processes have been heavily implicated in the domestication of animals and plants under human management: directed selection and genetic isolation (Larson et al. 2014). Directed selection refers to the advertent and inadvertent roles of humans in mediating the evolution of a species. Human-mediated selection can include spontaneous adaptations within anthropic environments (namely, the human niche), extensive land management and resource intensification practices, as well as intensive cultivation and husbandry. Genetic isolation refers to the limited ability of managed, cultivated, and husbanded animals and plants to interbreed with wild populations of the same or related species. Genetic isolation enables the accumulation of phenotypic and genotypic attributes within selected subpopulations relative to the parent population, namely, without continual dilution of selected traits resulting from interbreeding with wild populations. Genetic isolation is ordinarily achieved through moving a species outside of its natural range, as well as through the physical separation of managed from wild populations. Genetic isolation can also be effected by: the eradication of wild populations through environmental degradation and habitat

destruction, and through overhunting leading to local extirpation and extinction; the removal of pollinators through climatic, environmental, or anthropic processes; and, vegetative (clonal) reproduction of plants. The relative importance of directed selection and genetic isolation has varied for different animal–human and plant–human domesticatory relationships.

Domestication has been characterized as coevolutionary, namely a mutually beneficial relationship between people and a plant or animal. The mutual evolutionary benefit is demonstrated by the ability of a species to spread widely and outside its natural range, especially in comparison to ecological competitors. There are mutual influences for both parties within the domesticatory relationship, including the phenotypic (including behavioral) transformations to the animal or plant, and transformations to human behavior and social forms engendered by cultivation and husbandry.

Plants

The character of human–plant domesticatory relationships can be exemplified against a range of plant exploitation practices, including gathering to intensive cultivation. An increased intensity of human management, namely through levels of intervention in promoting the conditions for growth of plants, occurs as a result of tending and weeding, periodic pruning and burning to encourage new growth, as well as clearing of vegetation around stands of favored plants. Here, the level of human intervention in plant life cycles increases, with attendant human-directed selection of favored phenotypic traits among managed plants. The degrees to which these phenotypic preferences become more frequent within a population, as well as the degrees to which genetic markers of preferential selection practices become fixed, reflect numerous factors, including persistence of human practices and degree of interbreeding with populations not subject to the same degree of selective pressure. A stepped change in human-directed selection occurs with planting, including transplanting.

Domestication traits have been charted in archaeobotanical assemblages of cereals and legumes using grain size and prevalence of

nonshattering—many other phenotypic traits associated with domestication are not readily identifiable in the archaeological record (Table 1) (Fuller et al. 2014). Domestication as a process is considered directional and cumulative; namely, the relative frequencies of domesticated versus wild plants increase through time in archaeobotanical assemblages. The domestication episode refers to the period of directional change leading to “fixation” of a trait.

Animals

A wide range of animals have been domesticated by people, most notably mammals and birds, but also species as diverse as bees (*Apis* spp.) and silkworms (*Bombyx mori*). The domestication of mammals produced diverse phenotypic responses, including size reduction, cranial changes, horn-size reduction, coat color changes, decreased flight responses, increased sociality, earlier reproduction, and metabolic transformations, to name a few (Clutton-Brock 1999). People initially managed and domesticated animals for behavioral traits, with morphological transformations being a secondary outcome of management. The rationale and timings of animal domestication vary greatly across the globe.

Animals have been grouped according to three domestication pathways (Table 2) (Zeder 2012). Different pathways are possible for species that underwent multiple domestications, such as pigs (see PIGS). Alternatively, animals could be grouped according to the purpose of domestication, whether for animal products—such as meat, milk/blood, hide/fur/feathers—or for transportation and traction. The different ways in which animals are managed have implications for gene flow and the emergence of domestication traits.

Domestication and early agriculture

Evolutionary perspectives focus upon the directionality and fixation of phenotypic traits, as well as genetic correlates during domestication. Yet, questions remain in terms of clarifying precisely when domestication was initiated and when it ended. Rather than viewing species as having two forms—“domestic” and “wild”—for many species

Table 1 Comparison of domestication traits in sexually reproduced plants (including cereals and legumes) and vegetatively propagated plants (including root crops, sugarcane, and bananas).

<i>Trait</i>	<i>Domestication in sexually reproducing plants</i>	<i>Domestication in asexually reproducing plants</i>
Size of edible portion	Increased seed size in cereals, legumes, nuts	Increased size of edible portion, most marked in starch-rich plants
Ease of harvesting	Development of nonshattering seeds	Decreased seed size/suppression in some fruits
Timing of fruit production	Synchronous food production within plant and between plants of the same species	Potential development of bunching equivalent
Plant architecture	Apical dominance	Asynchronous and more continuous food production, with in-ground storage for some root crops
Plant life cycle	Shift towards annual life cycle based on sexual reproduction from seed	Apical dominance in some plants Shift towards perennial life cycle based on vegetative production of suckers, shoots, subterranean storage organs, and other viable plant parts
Photoperiod sensitivity	Loss of photoperiod sensitivity	Uncertain change to photoperiod sensitivity
Defensive adaptations	Loss of defensive adaptations (spines, hard seed casings, toxicity, acidity) to enhance harvesting, processing, and consumption Easily adapted to new environments	Loss of defensive adaptations (spines, hard seed casings, toxicity, acidity) to enhance harvesting, processing, and consumption Triploidy and vegetative propagation enable cultivation in wider environmental (altitudinal and latitudinal) ranges
Environmental tolerance		
Disease resistance	Reduced resistance to disease and pests due to human selection following continued sexual reproduction of subpopulation	Dramatic reduction in resistance to disease and pests due to low genetic variability in clonally reproduced cultivars
Palatability	Increased selection for desired traits	Increased selection for desired traits

Source: Based on information in Zohary and Hopf 2000; author's research.

Table 2 Domestication pathways for animals.

Pathway	Description	Examples
Commensal	Animals became habituated to people and the human niche, such as settlements, and gradually became embroiled in domesticatory relationships with people	Dog (<i>Canis familiaris</i>) Cat (<i>Felis catus</i>) Pig (<i>Sus scrofa</i>) Chicken (<i>Gallus gallus</i>) Ducks (Anatidae) Turkey (<i>Meleagris gallopavo</i>)
Directed	People used preexisting knowledge and practical experience of managing and herding animals to directly domesticate a species for a specific purpose or resource	Horse (<i>Equus caballus</i>) Donkey (<i>Equus asinus</i>) Camel (<i>Camelus</i> spp.)
Prey	Animals were originally hunted for hide, bone, and meat; people gradually began to manage animal populations to maintain hunting levels, which eventually led to more direct rearing and herding	Goat (<i>Capra hircus</i>) Sheep (<i>Ovis aries</i>) Cattle (<i>Bos taurus</i>) Pig (<i>Sus scrofa</i>)

Source: After Zeder 2012.

there is a continuum including “semidomesticated” and “domestication gradients.” To date, there has been an overemphasis on the evolutionary aspects of the domestication process in archaeology, with an underappreciation of environmental controls on genetic expression, such as epigenetics and plasticity (Larson et al. 2014).

In recent years, the number of “centers” of early domestication and agriculture has increased (Larson et al. 2014). This has led some to advocate a more decentered approach that focuses on the domesticatory relationships between people and other species in place and time. The presence or frequency of domesticates has been used to identify agriculture in the past, whereas more recent definitions shift to a reliance on the cultivation of plants and the husbandry of animals for subsistence to identify agriculture in the past. The conceptual shift is twofold: socially, the dependence of people on cultivated foods and managed animals is manifest in the ways they structure their lives and society; and, biologically, the emergence of domestication traits in animals and plants is influenced by a range of social and environmental factors.

SEE ALSO: Biogeography; Paleoethnobotany and Ancient DNA Analysis; Zooarchaeology and Ancient DNA

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Domestication of Equids

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The domestication of two equids—the horse and the donkey—enabled profound and lasting changes to human societies and economies. The use of these animals to aid transportation sustained larger interacting communities and enabled people, possessions, ideas, and diseases to circulate faster and more efficiently. An important factor in the development of mobile pastoralism on the Eurasian steppe, domestic horses (*Equus caballus*) were probably also pivotal in large-scale ancient migrations westward influencing the genetics and languages of Europeans until today. Likewise, domestic donkeys (*Equus asinus*) had an important role in the organization of early states and pastoral societies in North Africa and the Near East.

Current understanding views the earliest animal domestications as emerging unintentionally along gradual coevolutionary pathways, with later domestications often seen as more rapid products of deliberate human selection, in that once agriculture had emerged and spread, human communities were able to envisage other wild species as potentially desirable resources through domestication. Both horse and donkey are normally viewed as belonging to the latter category, emerging as domesticates in the mid-Holocene, although the process may have been slower and less linear than previously thought (Rossel et al. 2008).

Both horse and donkey domestications have been highly debated and controversial topics, in part because of the scientific challenges in identifying the early stages of domestication and the degree of coverage of archaeological research in the relevant regions. Although tensions still exist between different strands of evidence, multidisciplinary research is providing increasingly robust and detailed reconstructions. Animal domestications are investigated

through a range of techniques, especially the analysis of archaeological sites and finds, animal remains (zooarchaeology), and the genetics of both modern and ancient livestock.

Horse domestication

Horses are adapted to open grasslands with relatively poor habitat quality and strong seasonal variations in climate. They can tolerate cold, dry weather and also continue to feed during winters with deep snow. Around the time of domestication, the distribution of wild horse (*Equus ferus*) populations is thought to correlate with the distribution of open environments along the Eurasian steppes. Their main distribution was limited to the west by the more closed, wooded environments of Europe, and to the south by generally hotter and drier environments, although limited numbers of wild horses, likely relics of the Pleistocene distribution, did occur in small and sparse populations into the earlier Holocene in some areas of Europe and the Near East.

Wild horses were a common prey of hunter-fisher-gatherer communities along the Eurasian steppes. It is within this region that horse husbandry first emerged in the mid-Holocene. The Eneolithic Botai culture of northern Kazakhstan (ca. 3600–3100 BCE) has produced the earliest evidence for domestic horses from a series of substantial sites with high proportions of horse remains. Key evidence includes lipid residues from pottery indicative of horse milk, wear traces on horse teeth linked to harnessing, changes in the morphology of the bones, and probable corrals and use of horse manure (Olsen 2006; Outram et al. 2009). This indicates the multipurpose use of horses, for transport, meat, milk, and manure. The initial goals behind horse domestication are still debated; however, what is clear is that this earliest known horse husbandry is in a context where it was by far the dominant food animal, and horses' adaptation to the steppe region would have made them an ideal managed food source. The apparent absence of other domestic livestock from the

steppes of northern Kazakhstan at this time raises the possibility of horse domestication being an independent, indigenous innovation (Outram et al. 2009). A study of ancient DNA further indicates horse domestication on the Eurasian steppes prior to 3000 BCE (Ludwig et al. 2009). This identified a rapid and substantial increase in the number of coat colorations around this time, which is best explained by selective breeding after domestication. There is also the possibility of another domestication center on the Iberian Peninsula indicated by a combination of zooarchaeological and genetic data; however, whether this represents an independent event from the domestication on the Eurasian steppes, or simply the introgression of local wild stock into introduced domestic herds, is currently uncertain.

Genetic studies provide insights into the processes surrounding the origins and geographical diffusion of horse husbandry. Modeling of genetic data collected from modern nonbreed (local village) horses throughout northern Eurasia has identified domestication origins in the western Eurasian steppe, along with significant introgression from wild populations as horse husbandry spread (Warmuth et al. 2012). Further, modern populations of domestic horses demonstrate considerable mitochondrial DNA (mtDNA) variability (relating to maternal lineages) and extremely low nucleotide diversity on the Y-chromosome (relating to paternal lineages). This suggests the frequent incorporation of wild mares into domestic herds as horse husbandry spread; but not stallions, probably because they are less manageable. There is considerable diversity on the male-inherited Y-chromosome in samples from pre-domestic wild horses, indicating that reproduction from a limited number of stallions is related to the domestication process (Lippold et al. 2011).

Donkey domestication

African wild asses (*Equus africanus*) are adapted to arid and semi-arid environments, with physiological tolerance to limited water. They live in low densities and exhibit low sociability, both factors potentially linked with forage availability. Skeletal finds indicate that African wild asses were

occasionally hunted across northeastern Africa from around 20,000 years ago. This distribution extended across the Sahara and into northwest Africa until Roman times, and possibly into the Arabian Peninsula and the Levant (although the latter is uncertain; Marshall 2007). There are currently two recognized subspecies: the Somali wild ass (*E. a. somaliensis*) is critically endangered and is found in Somalia, Ethiopia, and Eritrea; and the Nubian wild ass (*E. a. africanus*) may now be extinct in the wild, but was found in northern Sudan and Eritrea (Kimura et al. 2013).

The earliest archaeological evidence for domestic donkeys comes from pre-dynastic Egypt. Body size decreases, interpreted as evidence for domestication, are recorded at the sites of El Omari (ca. 4800–4500 BCE) and Maadi (ca. 4000–3500 BCE) (Kimura et al. 2013). However, size decrease has been shown to be a relatively late indicator of donkey domestication (Rossel et al. 2008). The earliest evidence for transport use comes from ten articulated skeletons with paleopathologies indicative of overloading and strain found at Abydos (ca. 3000 BCE) adjacent to the mortuary complex of one of the founder dynasty Egyptian kings (Rossel et al. 2008). The elite context clearly demonstrates the cultural significance of these animals.

Genetic data from modern domestic donkeys identify two distinct mtDNA groups (clades 1 and 2), indicating their domestication from two separate wild populations. The Nubian wild ass has been identified as the ancestor of clade 1 donkeys; the geographical origins of clade 2 donkeys could include northeast Africa, the Maghreb of northwest Africa, and Yemen on the Arabian Peninsula (Kimura et al. 2010). A recent study by Rosenbom et al. (2015) assessed levels and patterns of genetic variation from different hypothesized areas of donkey domestication, with centers of origin being expected to retain more ancestral variation. They identified two areas as possessing the highest genetic diversity values: results from Sudan confirm the conclusions already reached by the mtDNA analyses; results from Yemen suggest another possible domestication event. The early presence of African wild ass or early domestic donkeys at Ash-Shumah (Yemen) during the mid-seventh millennium BCE further supports this potential (Marshall 2007).

A range of evidence, in addition to delayed body size change, indicates that donkey domestication was slow and complex. Genetic studies indicate Nubian wild asses sharing haplotypes with clade 1 domestic animals, possibly representing protracted and multiple recruitments of wild individuals, whereas the clade 2 network suggests a more restricted domestication event, involving a limited number of animals (Kimura et al. 2010; 2013). Ethnographic evidence indicates donkeys in Africa and Asia are rarely intentionally bred, due to a combination of wild ass behavior and human management strategies, although the practice of breeding domestic donkeys with wild asses in the early phase of domestication would explain the observed evidence (Marshall 2007; Kimura et al. 2013).

The integration of archaeological and genetic evidence indicates at least one domestication event in northeast Africa ca. 6,000–5,000 years ago. This occurred after cattle-based pastoralism had spread through the region. The subsequent retreat of the monsoonal rain front led to desiccation and desertification of the Sahara, forcing pastoral range changes and greater mobility. In these conditions, African wild asses clearly had advantages over cattle as domesticates for transport (Marshall 2007). The low number of early domestic donkeys at archaeological sites indicates they were not a primary food resource. The increasing aridity and the spatial distributions of cattle pastoralists and wild ass populations in northeast Africa present the likely context for domestication by mobile pastoral communities, rather than in the Egyptian Nile Valley (Marshall 2007).

Future directions

The complexities and challenges of studying domestication demonstrate the need to approach this through multiple, integrated techniques, as single methods offer overly simplified and biased views of the past. Methods that can give insights into subtly changing ecology, diet, and management, such as paleopathology and stable isotope analysis, deserve greater attention. Rapid advances have been made in recent years in the population genetics of domestic equids, and integrated archaeological approaches exploring

changes through time and space need to keep pace with these. For horses, for example, archaeological work is necessary to investigate whether horse husbandry in the Botai culture emerged abruptly or gradually from a local trajectory of intensifying horse management, whether it emerged earlier elsewhere, and whether or not any existing practice or knowledge of animal husbandry stimulated this transition in its emergent context. For donkeys, similar focus should be directed at those areas likely to have witnessed intensifying contact between ancient Saharan pastoralists and African wild ass populations during the desertification of the Sahara.

SEE ALSO: Dairying; Domestication; Zooarchaeology; Zooarchaeology and Ancient DNA; Zooarchaeology and Stable Isotopes

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Drugs and Psychotropics

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Theory

Biochemical mechanisms of plants and fungi generate a wide diversity of secondary metabolites that appear to have either adaptive or neutral survival value in the ecosystems in which these species have evolved. A large number of these natural compounds have mild to profound effects within the central nervous systems of *Homo sapiens*, and people have discovered many of their psychoactive effects empirically over millennia of interaction (e.g., see Schultes, Hofmann, and Rätsch 2002 for an extensive list of traditional human–psychoactive drug plant associations).

From ancient times, plant and fungi sources of bioactive substances have been used to heal or provide support in daily work, as well as to escape from life's harsh realities and inspire the ritualized development of spiritual beliefs. Indeed, there are a relatively large number of psychoactive drug plants and fungi that appear to have had ancient mind-altering relationships with humans. Many of these have been documented in the archaeological record from numerous parts of the world, although the degree of archaeological evidence supporting these prehistoric and historic relationships varies significantly.

How and why have humans developed long-term relationships with these kinds of species? In many modern societies, people generally dismiss “divine visions” as hallucinations that are unreal, and the yearning to experience a direct communication with a supernatural force is frequently construed as an indication of mental disorder. Nevertheless, some scholars and scientists assert that such visions and communications are fundamentally associated with an

ancient and ongoing pan-global cultural tradition involving the use of mind-altering experiences to produce profound, more or less spiritual and cultural understanding (e.g., see Bourguignon 1973; Schultes et al. 2002; Merlin 2003; Clarke and Merlin 2013). This enduring human connection with various psychoactive plants and fungi is a relationship of great antiquity. It may have even originated before the evolution of our own genus, but almost certainly within the temporal span of our own species dating back into the Pleistocene.

A fundamental model of how and why humans have long used psychoactive plant or fungi materials for spiritual reasons was well articulated half a century ago, when anthropologist Weston La Barre responded to a rhetorical question posed to him by the Harvard ethnobotanist Richard Evans Schultes. Within his response, the Duke anthropologist La Barre (1970) contended that people, at least in polytheistic contexts, have been “culturally programmed” to find plants (or fungi) that facilitate communication cognitively with their spirit world. La Barre suggested that this custom had its origins in the Paleolithic Era, well before the rise of cultivation, when all humans were hunters and gatherers. According to his proposition, as bands of humans dispersed into new regions, including new ecosystems, they brought with them a culturally inspired motivation to identify and utilize species of plants or fungi that would allow them to transcend their “normal” perceptions and empower them to communicate with their ancestors or deities.

In modern societies, psychoactive materials are used in a variety of ways. These include religious, medical, and secular applications, which in ancient times may or may not have been viewed as separate. For example, in the case of Neolithic Europe, some have argued that psychoactive substances were often consumed in a spiritual context, which would have included therapeutic uses too, because it would have been artificial to separate bodily healing from ritualistic observance. However, it has also been suggested that evidence for the consumption of mind-altering substances in the past,

such as THC-rich cannabis or morphine-laden opium, should not necessarily be interpreted as a manifestation of either deep ritual importance or utilization for largely pleasure-seeking purposes; such drugs “may simply belong to the material medica” (Sherratt 1995). For example, small opium poppy fruit capsules dated to the early Neolithic, which were placed in small woven bags and set next to human bodies in a burial cave in southern Spain, most likely were put there because of their pain-alleviating potential and/or as a source of psychoactive power to help the deceased’s progress to an afterlife (e.g., see Becerra Romera 2006; Gavilán Ceballos 2008).

In any case, under diverse conditions of non-industrial societies, psychoactive substances were apparently often used in ritualistic, religious contexts; for whatever purposes, the widespread ancient human use of mind-altering species has been documented archaeologically (e.g., see Merlin 2003; Clarke and Merlin 2013). It is also essential to remember that ingestion of psychoactive substances can produce a variable altered state of consciousness depending upon the quality and quantity of the mind-altering compounds eaten or imbibed, the psychological set of the user, and the social–environmental setting in which the substance is consumed.

Methodology

Data used to support the widespread ancient use of psychoactive drug species can be found in the literature across various disciplines, such as anthropology, archaeology, paleoethnobotany, palynology, ethnobotany, and history. Dating of evidence varies in technique and relative reliability depending on the type and quality of the specimen. Most samples, because of their organic nature (e.g., seeds, charcoal, fibers), have been dated using the radiocarbon method (e.g., El-Seedi et al. 2005), while others such as pottery can be dated using luminescence techniques (Fitzpatrick et al. 2009; see DATING CERAMICS AND LUMINESCENCE). Other chronological documentation has relied on reference to the written record, sometimes in conjunction with iconography. The archaeological evidence for psychoactive drug plant research has traditionally come in two

forms: artifacts and plant remains. The advantages and disadvantages of both forms of evidence must be considered.

All artifacts are subject to some type of interpretation and reconstruction. Differences in interpretation may arise concerning the specific identification of the organism that the artifact is supposed to represent, its association with other archaeological remains, and interpretation of its artistic, religious, medicinal or other practical or psychological uses. The paleoethnobotanical record (see PALEOETHNOBOTANY) is usually much less subjective. However, difficulties in assigning specimens to specific taxa may occur, and confirmation of its alleged use by humans is also sometimes difficult or even contentious, particularly if the context in which the remains are found is unclear. The most dependable information should be a supportive combination of the two types of archaeological evidence. Although ideally scholars should identify the symbolic meanings intended in species depictions manifested in artifacts, along with their microfossil or macrofossil presence in related archaeological sediments, the discovery of this type of corroborative evidence has been rare. Much of what is known from Europe is paleoethnobotanical, while in other areas such as the Near East and East Asia, the evidence, at least until recently, has usually been limited to artifacts and interpreting their function and meaning. This reflects the focus, history, and relative technological sophistication of research undertaken by archaeologists working in these respective areas.

Artifact interpretation may vary between different schools of archaeological theory, or simply may differ in the identification of what species is represented. For example, an evolutionary theorist may be hard-pressed to refer to a clay figurine as a religious object because it appears to have enormous breasts and hips; or artifacts depicting globular “fruit” may seem to some to be representations of opium poppy (*Papaver somniferum* L.) capsules, but to others they look like depictions of pomegranate (*Punica granatum* L.) fruits (Merlin 1984). However, any interpretation without convincing supportive evidence may be premature or inaccurate. Documentary evidence is usually not available. Therefore, a prudent interpretation of archaeological remains must

take into account the context and associations of the artifact within the site.

Paleoethnobotany is a subfield that seeks to explain human–plant relations over time through the identification and analysis of archaeological plant remains. Historically, some macroscopic plant remains that were discovered and removed from ancient sites in the early stages of archaeological research were not appropriately extracted from undisturbed (in situ) contexts; for example, a series of ancient opium poppy (*P. somniferum* L.) capsules (referred to above) found in southern Spain, and many ancient opium poppy seeds from various central European sites, were not recovered from well-sealed closely dated deposits (Merlin 1984). While these remains can normally be dated as precisely as possible, accurate determination of their prehistoric contexts is often disputable; nevertheless, they are currently still some of the most direct early evidence of the presence and probable use of this species in the region (also see Jiang et al. 2006 for recent remarkable discoveries of ancient *Cannabis* remains associated with humans).

Future Research

Albeit still somewhat fragmentary, the archaeological and paleoethnobotanical records, along with evidence from “historical contextualization”, offer broadly-based geographical and ethnobotanical confirmation for a very widespread, deep time model of human use of psychoactive substances. Precisely when people initially decided to consume a psychoactive substance will most likely remain unknown due to the vagaries of preservation of artifacts and especially organic materials. Nevertheless, archaeologists now have the unique opportunity to extract more information from ancient subfossil and fossil remains; the antiquity of such remains may date back hundreds or even thousands of years in contexts that can offer more meaningful interpretations of their ancient relationships with people. The expertise of scientific recovery, identification and analysis of ancient mind-altering substances, and the paraphernalia used to ingest them, has improved dramatically in recent years. This exponential increase in data recovery and informed interpretation has been facilitated by improved techniques

in various natural science disciplines, as well as archaeology. Archaeologists and paleoethnobotanists can now better document and explain depositional stratigraphy, clarify the composition and utility of artifacts, more accurately identify micro- and macrobotanical remains, and describe and interpret ancient environmental parameters and human skeletal remains with greater methodological and theoretical sophistication. Using powerful tools of modern science and human imagination, along with remaining ethnohistorical explanations and ethnographic accounts, our understanding of humans’ deep-rooted desire to experience “ecstasy” in the original sense of the word (to break the mind free from the body and communicate with the “gods” or the ancestors) is becoming stronger over time.

SEE ALSO: Beverages; Dating Ceramics and Luminescence; Grapes and Viticulture; Paleoethnobotany; Palynology

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Environmental Archaeology

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Introduction

Environmental archaeology is the study of people and their interaction with the environment over time. It involves the application of the natural and physical sciences to the study of biological remains and to the deposits in which they are preserved, for the purpose of understanding how people both shaped and were shaped by their environment over millennia. Environmental archaeologists are concerned with how people obtained the necessities of life—food, drink, warmth, and shelter—and how, in doing so, they altered the world around them; these are often referred to as paleoeconomic questions. At the same time, they are interested in how the environment has changed over time through natural and human induced climate change and how plants and animals have adapted and evolved as a result of these changes, often referred to as paleoecological questions. They are also concerned with human behavior, especially how people related to, and perceived, landscapes and living things through space and time.

Key areas of interest include processes of domestication (see DOMESTICATION) and the development of farming; the use of natural resources in craft and industry (for example, metal production and working, and pollution arising from these activities; the creation of cultural landscapes and novel environments (see URBAN ENVIRONMENTS); the role of animals and plants in ritual and belief; how humans respond to environmental changes such as sea-level change and natural disasters. The study of people themselves—especially diet, health, and disease—and geoarchaeology are included within the scope of environmental archaeology, though some regard these as somewhat separate

disciplines. However, the approach taken here is a holistic one, which regards humans and their culture and behaviors as part and parcel of the ecosystems they inhabit (Evans and O'Connor 1999, 1; Butzer 1982).

Preservation and recovery

Fundamental to environmental archaeological research is an understanding of taphonomy and formation processes, from the microenvironment of an artifact, archaeological context, or deposit to processes operating at the scale of an individual site, of a region, or even globally. In order to establish what kinds of research are possible, environmental archaeologists need to know what types of biological remains are likely to be present in a particular location, how these remains are likely to be preserved, and how they entered the deposit. Taking a different approach, they may start with a research question or hypothesis and then target those sites and environmental evidence that can best answer the question posed.

Paleoenvironmental questions are best addressed through the investigation of naturally accumulating deposits, where direct human input is limited. Such deposits are often called paleoenvironmental archives, and the investigations carried out on them are known as off-site or paleoecological studies. However, even within seemingly natural or pristine environments, humans will almost certainly have been operating in the past. For example, lakes will have been fished and will have supplied drinking water for people and animals. Occupation is likely to have occurred at the lake edge and on islands within the lake. People may even have constructed artificial islands or platforms within the lake itself. It is vital that these possibilities are considered when undertaking work at such sites, so that the influence of these activities can be taken into account as part of any investigation.

Where the principal aim of the research is to answer paleoeconomic questions or to explore social relationships with plants and animals, on-site studies are usually preferred. Ideally

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the types of deposit chosen are those that both formed and were sealed rapidly and where there is little or no evidence for intrusive or residual material, for example, a pit that was dug, filled up with rubbish from activities happening nearby, and then sealed. However, the suitability of the context will depend on the types of question posed as well as on the nature of the archaeological record at that time and location. What is vital, however, in both on-site and off-site studies, is an understanding of how the various types of material ended up in the deposit and what happened to them after they entered it.

A key distinction here is between material that formed in situ and lived in the deposit (the structure itself and the organisms living on it or in it) and material that entered the deposit or structure from the outside, either as a result of natural processes such as wind and rain or as a result of human agency, which may be deliberate or incidental. The former kind of remains are referred to as *autochthonous* (from the ancient Greek adjective *autochthonos* “from the same land,” itself a compound of *autos* “same” and *chthōn* “earth, land, territory”)—for example, seeds from plants that grow on the surface of a deposit, or insects living in a building; the latter kind of remains are referred to as *allochthonous* (from the ancient Greek adjective *allochthonos* “from another land, foreign,” a compound of *chthōn* with *allos* “other, different”). *Allochthonous* material includes for example, seeds washed or blown in from the surrounding area, plant “waste” from crop processing disposed of in a pit (deliberate deposition), or seeds that end up in a cesspit having survived passage through the human gut (incidental deposition). The ways in which *allochthonous* material may enter a deposit are myriad. In addition, such material may be derived from a variety of sources, either close to the point of deposition or at a considerable distance from it. Material of different ages may also end up in the same deposit, for example, wood used on a fire might contain wood from a demolished structure of considerable age, driftwood may be collected from the shore along with kindling from local heathland collected earlier that week. Disentangling these formation processes is an essential part of analysis and interpretation.

Another important factor is knowledge of what has been lost because it failed to be preserved.

Broadly speaking, permafrost conditions, very arid conditions, and conditions of oxygen depletion (anoxic or anaerobic deposits) result in the excellent preservation of a wide range of biological remains over thousands of years. Outside these extremes, the preservation of biological remains is influenced by the pH of the deposits, the depth of the burial, temperature, and fluctuations in moisture content. For example, animal bone and mollusks survive well in oxic deposits where the pH is > 7.0 , whereas pollen will not survive. In contrast, in oxic deposits where the pH is < 5.5 , bone—unless calcined as a result of burning—will not be preserved, whereas pollen will be well preserved (Campbell, Moffett, and Straker 2011, fig. 1; Evans and O'Connor 1999, 80–81). Plant remains preserved by charring (carbonization), wood charcoal included, will survive well in most deposits, unless subject to mechanical weathering such as repeated wetting and drying or freeze–thaw processes (Miksicek 1987).

In addition to considering whether broad categories of remains will be preserved at a site, the differential preservation of different parts of organisms or between different organisms needs to be taken into account. For example, where crops such as cereal crops are exposed to fire as part of being processed into food for humans, they will have a greater chance of being preserved by charring and of becoming part of the paleoethnobotanical record. By contrast, remains of leafy vegetables will be preserved relatively rarely, for instance, through desiccation, or as a result of anoxic conditions; and even then it may be difficult to distinguish them from other plant leaves (van der Veen 2007). In some contexts preservation conditions may be such that only more robust remains are preserved. For example, pollen from lime trees (*Tilia* sp.) will survive much better than pollen from beech trees (*Fagus* sp.), while fern (Pteropsida) spores are particularly resistant to decay (Wilkinson and Stevens 2003, 94; Bunting and Tipping 2000). For these reasons, it is necessary to carry out preservation or condition assessments in order to determine the extent of postdepositional bias for a given assemblage (Bunting and Tipping 2000).

Processes of excavation, sampling, and recovery will also influence the nature of assemblages. Oyster (*Ostrea* sp) shells generally survive

excavation more or less intact, while shells of the common mussel (*Mytilus edulis*), preserved whole in the ground, will break up on excavation because the parts of the shell are very fragile (Winder 1980). Charcoal will further fragment, if wet sieved or floated. The elements and range of species of animal bone recovered will depend on the minimum mesh size used when sieving samples (Baker and Worley 2014, figure 7).

A useful way to approach the recording of preservation and taphonomic evidence is to run the taphonomic trajectory in reverse, starting with the assemblage as observed in the laboratory and considering how the observations made relate to the effects of excavation and recovery strategies, the processes that occurred after deposition (burial), and the processes that took place between the death of the organism and its burial, including cultural processes. Once these effects are accounted for, the environmental archaeologist will have a much better understanding of the original living organism or group of organisms that the assemblage s/he is studying represents (O'Connor in Baker and Worley 2014, 27–8).

Identification and interpretation

An accurate determination of the biological remains to the lowest possible taxonomic level—be that variety, subspecies, species, genus, or family—is fundamental to the practice of environmental archaeology. To identify their material, environmental archaeologists use a combination of identification guides and modern comparative references collections, along with published identification criteria developed for particular classes of remains. In doing so, they accept the premise that species living today are analogous to those that were living hundreds or thousands of years ago and that they have had similar physiological requirements to those of the species alive today—notwithstanding that processes of change such as those that occur as a result of domestication and the introduction of new species into novel environments are the very topics that the discipline seeks to investigate. Hence whether a living species can be regarded as the equivalent of a species with the same characteristics recovered from deposits thousands of years old is one of the

hypotheses that needs to be tested as part of the research process (Dincauze 2000, 29).

Related to this concept of analogical reasoning is the principle of uniformitarianism, often summed up by the phrase “the present is the key to the past.” This idea was first postulated by the geologist James Hutton and further developed by Sir Charles Lyell. The core of this principle is that the natural processes that take place on earth today are the same as those that operated in the past and produce the same effects. Thus sequences of deposits that characterize meandering rivers today will have the same characteristics and will have formed as a result of the same processes as deposits observed within the geological and geoarchaeological record. Although it is now recognized that natural processes that occur in the present are not directly equivalent to those that operated in the past, especially in terms of scale or duration, and that some environments that existed in the past do not exist today, this concept, modified to take account of these observations and termed *methodological uniformitarianism* by Stephen J. Gould, remains central to paleoenvironmental reconstruction (Dincauze 2000, 30; Wilkinson and Stevens 2003, 28–31).

A natural consequence of this way of thinking is the idea that organisms can be used as proxies for the environments in which they occur. Thus, if bones of reindeer and woolly mammoth are recovered from a deposit currently within a temperate environment, the existence of cold-climate conditions at the time when the deposit was forming can be inferred (Dincauze 2000, 30). Some species have very precise requirements; for example, some parasites need specific hosts in order to complete their life cycle, while some insects will only feed on a single plant species. Such species are termed “indicator species,” since they show the presence of the plants on which they feed or animals they infect. However, in many cases, an indicator species, although typical of a particular habitat, will also be found in similar places, tolerating a range of environmental conditions. In addition, some species may have lived in environments that existed in the past but for which there is no modern equivalent.

An example of this is the seaweed fly (*Thoracochaeta zosterae*). This fly is currently found only along the marine shoreline within decomposing seaweed. However, its puparia are frequently

recovered from medieval and postmedieval cesspits. This prompted a number of hypotheses: (1) *T. zosteræ* was able to live in medieval cesspits, feeding on sewage; (2) seaweed was being imported into medieval towns; (3) *T. zosteræ* had altered its environmental requirements between modern and medieval times; or (4) a closely related, undescribed species of *Thoracochaeta* that feeds on sewage existed in the past and became extinct, or has as yet to be recorded. Taxonomists established that the archaeological and modern flies were indistinguishable from each other and therefore should be considered to be the same species—dismissing one hypothesis. Isotopic analysis of $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ ratios, in both the modern and the archaeological puparia, and their likely larval food, seaweed and sewage respectively, showed that the modern flies had a marine diet, whereas the archaeological flies had a terrestrial diet. This indicated that *T. zosteræ* formally inhabited medieval cesspits, feeding on sewage. It is thought that medieval open cesspits that would have contained both wet and drying decaying matter were ideal for *T. zosteræ*, unlike modern closed cesspits, which remain constantly wet. Thus it is clear that the seaweed fly used to thrive in a habitat for which there is no modern equivalent and that its presence in medieval towns does not provide evidence for the presence of seaweed (Webb, Hedges, and Robinson 1998).

Because of the need to take such complexities into account, researchers, rather than relying on single species, consider assemblages as a whole, recording the range of taxa present and their relative abundance. From this, and with reference to ecological data and ethnographic data, indicator packages (see ARCHAEOENTOMOLOGY), taxocenes (see LAND AND FRESHWATER MOLLUSCS), and transfer function methods have been developed. These consider the communities of different types of biological remains that occur together, and in roughly the same proportions, as indicative of particular environments, and are continually being refined through studies of modern analogues and as more paleoecological data becomes available.

In tandem with these methods, a multi-proxy approach, whereby different lines of environmental evidence are brought together to arrive at more accurate and nuanced interpretations of the paleoenvironmental record,

is generally employed. This allows for differences in the responses of different groups of organisms to be taken into account, including rates of colonization and varying competition. For example, the presence of alder leaf beetle (*Agelastica alni*) in a deposit formed within a paleochannel indicates the previous existence of alder with the catchment. The relative abundance of alder pollen, as compared to the pollen from other trees within the same deposit, could suggest the likely extent of alder growth within the catchment and what other trees were growing in the area. The recovery of macroscopic plant remains of alder, such as seeds, catkins, and buds, could indicate that alder was growing on the banks of the channel, and even in rapidly accumulating deposits; and it could suggest the season when the deposit formed. In addition to this evidence, remains of chironmids, ostracods, mollusks, and diatoms preserved within the same sediments could be used to explore water quality in the former channel and to provide information on depth, flow, substrate, and nutrient status.

Similar approaches and methods can be used to answer paleoeconomic questions. Multidisciplinary studies of dairying have employed a combination of zooarchaeological methods, stable isotope analysis, and organic residue analysis of ceramics to understand the evolution of dairying practice. A combination of different methods can also be employed to understand human behavior, including single events, for example a bustum burial at Biddenham Loop, Bedfordshire, England. Through integration of human osteoarchaeological, zooarchaeological, charcoal, and artifactual evidence from the burial pit, it was possible to establish that the adult male was laid on the pyre in an extended position, with a dog placed at his feet. Charcoal found in association with iron nails in the same feature suggested that the corpse may have been laid on a decorated funeral bed (Baker and Worley 2014, 44).

Future directions

Advances in biomolecular techniques, in particular next-generation sequencing of DNA, the development of stable isotope analysis, and organic residue analysis, have opened up new avenues of environmental research,

allowing us to address questions concerning the evolution of animals and plants, domestic species, biogeography, diet, and environmental change in far more detail than was possible even 10 years ago. At the same time, the application of computational modeling techniques, which allow the testing of different scenarios in paleoenvironmental reconstruction, has revealed considerable potential as well as shown the limitations of our data.

Research by archaeoseismologists and archaeovolcanologists is helping people who live in earthquake zones and in areas with active volcanos to understand the biographies of people from those places and to provide information to hazard managers and disaster planners. Environmental archaeology can also inform responses to climate change, not only in terms of heritage management but also by offering lessons from the past that can be used to inform climate adaptation measures and to suggest how to tackle pollution. This has prompted the suggestion that environmental archaeologists should play a greater role in debates concerning the future of humans on planet Earth and be more upfront about their ethical stance (Riede, Andersen, and Price 2016).

Humans are capable of adapting to a wide range of environments; they are ecosystem engineers par excellence. Understanding the ways in which people have coped with disasters and environmental changes in the past, including embarking on huge cultural changes, shows that the future holds a wealth of possibilities for solving the challenges humans face at the start of twenty-first century.

SEE ALSO: Air Pollution; Archaeological Volcanology; Archaeoseismology; Biogeography; Charcoal and Wood Analysis; Dairying; Disaster Archaeology; DNA: Next Generation Sequencing; Flooding; Formation Processes; Geoarchaeology; Glacial and Periglacial Environments; Lake Deposits; Organic Residue Analysis; Paleoenvironmental Reconstruction; Paleoethnobotany; Palynology; Peat Deposits; River Systems; Sampling in Environmental Studies; Sea-Level Change; Taphonomy; Temperate Environments; Use of Biological Collections; Vegetation Modeling Using Pollen Data; Water Pollution; Zooarchaeology

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Environmental Management with Fire

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The systematic use of fire to manage the environment is one of the most ecologically important behavioral characteristics of humans. Fire consumes vegetation, differentially inhibits plant growth and reproduction, and modifies soil properties. It is a key ecological disturbance and evolutionary force in nearly every terrestrial biome on Earth. Humans are the only animal to master the use of fire and this ability has enabled humans to completely transform landscapes.

As ecosystems engineers, humans habitually modify their environments through daily provisioning. Fire has long been a key component of human provisioning strategies, facilitating efficient manipulation of the distribution, productivity, and diversity of natural resources. The use of fire helped to broaden the reach of human activity to the landscape scale. It was with the ability to set fires that humans first became agents of broad-scale ecological disturbance.

At the site-scale, evidence for hominin fire-making is documented between 1.5 to 0.3 Ma, predating the emergence of anatomically modern humans. As a requisite to sustaining hearth-confined fire, humans learned to “feed” fuel to embers or ignited tinder. Given the cognitive processes involved in learning to master fire in this way, it is difficult to imagine that the confined use of fire significantly predates the casual setting of landscape fires. Armed with the knowledge and skill to ignite fires, humans eventually learned how to selectively broadcast fire across the landscape by taking advantage of weather and topography through the precise timing and placement of ignitions. This step in our relationship with fire allowed for the transformation of fire use from simple environmental disturbance to a powerful tool of environmental management.

Fire use rationale

Historical and contemporaneous human groups have been observed using fire in a myriad of ways and in a variety of environments. Fire is used by hunter-gatherers in both immediate and delayed return foraging contexts. The scale of environmental consequences of the use of fire by hunter-gatherers remains highly debated. Among hunter-gatherer groups who have been documented using fire, immediate return hunting is one of the most commonly cited reasons. For hunting, “game drive” fires are set in order to flush prey from the cover of trees and shrubs. For example, the Paiute of the North American Great Basin historically used fire in sagebrush range to encircle black-tailed jack rabbits (*Lepus californicus*) and drive them toward a group of men, women, and children armed with clubs (Steward 1938). Paiute also used fire to flush larger game such as pronghorn antelope (*Antilocapra americana*) and deer (*Odocoileus* spp.) into the open from forested portions of the mountains. One of the most cited examples of the historical use of fire to manage the environment is the “fire-stick farming” of Australian Aboriginals (Jones 1969). In the western desert of Australia, the Martu people continue to use fire to burn mature spinifex (*Triodia* spp.) savanna for locating small burrowed game such as the monitor lizard (*Varanus indicus*) (Bird, Bliege Bird, and Parker 2005).

Many hunter-gatherers groups also used fire to improve the productivity of commonly foraged pyrophilic and fire-tolerant vegetation such as berries, tubers, and nut-bearing trees. In California, Native American groups used fire along with coppicing to encourage specific morphological traits in fibrous plants harvested for basketry, cordage, and other purposes (Anderson 1999).

Probably the most common use of fire today is for preparing agricultural fields before planting or after harvesting. Fire prepares soils for planting by clearing unwanted biomass and converting it into charcoal (carbon) and potash (potassium) which serve as nutrient amendments that

help increase an agricultural plot's productivity. Agricultural uses of fire date to the very beginning of the Neolithic and are likely to be associated with domestication at the species level and coevolutionary processes at the agro-ecosystem level. Agriculture fire use is extremely diverse ranging from annual stubble burning to fire-fallow cultivation. The latter group of practices goes by many names, for example slash-and-burn, swidden, shifting cultivation (Conklin 1961). Fire-fallow generally involves cutting and burning brush and trees from a plot just prior to planting cultigens. Although new plots can be cleared from old growth forests, fire-fallow most often involves the clearance of secondary forest or seral vegetation.

Pastoral fire is another widespread practice. Pastoralists burn grasses and shrubs in order to encourage the growth of more palatable vegetation. Importantly, combusted biomass provides carbon and potassium as soil amendments, often improving pasture productivity. Pastoral fire regimes involve frequent, low-severity fires that help grasses to outcompete shrubs. Many heathlands, subalpine pastures, and savannah landscapes are maintained by the frequent application of fire.

Socioecological dynamics

Weather, topography, and fuel characteristics control variability in fire spread and intensity which, in turn, determine the severity of fire effects on the environment (Agee 1993). Some landscapes maintained by human fire use involve extensive, low-severity fires that inflict minimal disturbance on ecological conditions. In the subalpine altitudinal zone of the western Pyrenees (800–1600 msl), Basque pastoralists set fires in the late winter and early spring. Today, pastoral fires prevent processes of ecological succession and mitigate selective forces of grazing and browsing, thus maintaining a relatively stable forest-pasture landscape mosaic. Over the long term such fires converted large areas of forest to pasture and significantly altered the properties of soils in ways that facilitate their use and conservation. The emergent human-fire-landscape dynamic is self-organizing in that it requires

little if any active fire management or suppression beyond consideration of the timing and placement of ignitions by individual farmers. Fires follow pathways through the landscape predetermined by vegetation, specific weather conditions, and topographic microclimates. The landscape patterns that emerge from pastoral fire use help to structure land tenure at the community-level and constrain the nature and potential of household-level land holdings (Coughlan 2014).

In other landscapes, smaller, moderate to high severity fires maintain a fine-grained patchwork of early and late successional vegetation, through a rotational firing of land. In these landscapes fire achieves a metastability of pattern and process over the long term. For example, the use of hunting fires by the Martu of Western Australia scales landscape mosaic in ways that increase heterogeneity, biological diversity, and buffer climate-driven disturbances. Martu fires are smaller than the natural regime of lightning-caused fire, in part, because the Martu light fires under more moderate fire weather conditions. Over time, patterns of residential mobility and hunting-fire practices interact to form an emergent mosaic of fuel conditions that helps self-limit human- and lightning-ignited fires. The resulting pyrodiversity helps structure inter- and intragroup socioeconomic relationships for managing productive landscapes across generations (Bird et al. 2016).

Archaeological investigations, multi-proxy and multiscale

Archaeologists routinely study the traces of manipulations of the environment that evidence subsistence strategies, social organization, and beliefs. The archaeological investigation of fire management began in the 1920s with Grahame Clark's multidisciplinary approach to Neolithic settlement in Europe (Clark 1947). Clark incorporated settlement archaeology with studies in palynology (see PALYNOLOGY), sedimentary charcoal (see CHARCOAL AND WOOD ANALYSIS), and ethnoarchaeology (see ETHNOARCHAEOLOGY) to posit Neolithic forest clearance by fire-fallow cultivation.

Yet, in spite of nearly 100 years of study, archaeologists have spent relatively little time investigating management using fire. This deficiency may relate to the fact that archaeological investigation tends to take place at the site-level. Although site-level data such as paleoethnobotanical remains (see also PALEOETHNOBOTANY) provide an important form of evidence for understanding the ancient use of management fire, the study of off-site fire use inherently requires a landscape perspective.

More robust studies of fire use take a multiproxy approach and often include methods from paleoecology such as palynology, magnetic susceptibility (see MAGNETIC SUSCEPTIBILITY), phytolith analysis (see PHYTOLITH ANALYSIS), and stable isotopes in paleoethnobotany (see PALEOETHNOBOTANY AND STABLE ISOTOPES). One key development in the last few decades involves the analysis of sedimentary charcoal (microcharcoal). Clark and Royall's (1995) study of charcoal sediments from Crawford Lake in Ontario, Canada was foundational in this area. Clark and Royall show that changes in forest composition are associated with ancient occupation of the area by Iroquois peoples. Importantly the authors link archaeological evidence for Iroquois land use with evidence for increased fire activity. Research efforts that combine studies of sedimentary charcoal with archaeological investigations are now underway in a number of areas.

A major limitation to the use of sedimentary charcoal has been the fact that the high-altitude lacustrine environments that provide reliable sedimentary archives are normally on the peripheries of human land use. As a consequence, investigators have sought out archaeological sites in proximity to lower resolution sedimentary archives found in bogs, mires, and colluvium. Mismatches between paleoecological and archaeological scales of investigation present challenges for combining these data, however modeling efforts may yet resolve such analytical difficulties.

Dendrochronological evidence for fire is another area in which proxies for changes in fire frequency can be linked with archaeological or ethnohistorical evidence of occupation. Recent studies evidence past fire use and management in North American ecosystems as diverse as

the temperate rainforests of the Pacific Northwest, California central coastal Redwood forests, Eastern Oak-hickory woodlands and the montane Ponderosa Pine forests of New Mexico. Dendrochronological research is of interest to archaeologists because its resolution is subannual and it can often provide information on both climate as well as local environmental conditions.

Due to the relevance of ancient management fires to paleoecological reconstruction, many studies involving past human-caused fires have proceeded without the aid of archaeologists. As a consequence of this legacy, the relationship of fire use to the archaeological record remains largely obscured. As reviewed above, archaeologists have begun to address this gap. In part, this has been accomplished through participation in collaborative, interdisciplinary environmental science projects. Moving forward, archaeological science must continue to refine methodological approaches to understanding how peoples in the past used fire to manage their environments.

SEE ALSO: Environmental Management with Livestock; Paleoenvironmental Reconstruction

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Environmental Management with Livestock

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Since their domestication, livestock have been important in shaping vegetation and landscape. Animal husbandry was introduced into the mostly forested landscapes of northern Europe around 6,000 years ago. Knowledge of the influence of livestock (see CATTLE and SHEEP AND GOATS) on the environment through time has especially been gained through palynology (see PALYNOLOGY), but also analysis of other environmental proxies such as insects (see ARCHAEOENTOMOLOGY) and macroscopic plant remains from lake deposits (see LAKE DEPOSITS) and peat deposits (see PEAT DEPOSITS). Palynological studies show that gradually—and following technological development and societal changes—the landscape was opened up, and managed woodlands, pastures, heathlands, hay meadows, and cultivated fields developed (Behre 1988; Krzywinski, O'Connell, and Küster 2009).

Large areas of the earth's surface are not suited to cultivation; for example, in Norway only three percent of the land surface consists of good-quality arable land, resulting in reliance upon livestock and extensive grazing and fodder collection in semi-natural habitats as part of pre-industrial food production. At the same time, the success of cereal cultivation (see WHEAT and BARLEY, RYE, AND OATS) in the past depended on the presence of livestock that produced dung for manure. Thus, a system of optimal environmental management developed in different geographical areas depending on the available natural resources. These semi-natural habitats, or outfields, are often rich in species and are today in danger of disappearing. With Norway as an example, we present four types of semi-natural habitats—mountain pastures and grasslands,

hay meadows, managed woodlands, and coastal heathlands—that were of vital importance to the traditional farming economy found in many places in the world with comparable landscapes, and in remote areas even today.

Mountain pastures and grasslands

In Norway, seasonal grazing of mountainous areas was traditionally organized as “summer farming.” It kept the livestock away from areas close to the settlements where the main production of crops and winter fodder took place, and made use of the resources of remote parts of the farm. Mountain grass productivity can be very high, and the best way to exploit this resource is to keep the livestock in these grasslands during the summer. The cattle had their calves in spring, and thus milk production was at its highest when the animals had access to the best fodder. To look after the cattle, people stayed in small cabins at the summer farms during the grazing season. The products (mostly cheese and butter) were transported regularly down to the main farm. Many farms had several temporary stations where they kept the cattle for some weeks during late spring/early summer until conditions became favorable at higher altitudes. Some of these areas were used for haymaking late in the summer before the cattle were taken down for the winter.

Archaeological and botanical evidence indicates that grazing in mountainous areas was already taking place 4,000 years ago in some places. It is, however, not until the fourth century CE and later that house remains are found at summer farms. Paleoecological studies indicate that the development of the historical grazing landscape at the summer farms started at about the same time. Probably these findings are related to the settlement history in corresponding areas at lower altitudes. Iron Age mountainous land-use probably differed from later specialized dairy farming (see DAIRYING), but the impact on the vegetation and the landscapes was very much the same.

Hay meadows

In temperate areas, hay has been an important winter fodder for millennia. As most of the arable land was needed for crop production, much of the hay had to be procured elsewhere. This was mainly done by cutting “hay” from flood meadows, naturally fertilized by flood water from rivers, or from semi-natural grasslands. These grasslands were never plowed or fertilized, although surface stones were removed to facilitate mowing. Natural fertilization occurred through grazing in early spring or autumn, to allow the hay crop to grow until July when haymaking normally started, but the most remotely situated meadows were not harvested until late in the summer. Many places had small barns within the meadows to store the hay temporarily. Fens were also mown, but they were only harvested every second or third year. As a result of these management regimes, in particular the exclusion of livestock at certain times of year and the taking of hay crops, these grasslands developed into semi-natural habitats of high biodiversity. Even today some of them rank among the most species-rich biotopes in Europe (Wilson et al. 2012).

Multivariate data analysis, modern analogs (surface pollen samples), and high-resolution pollen identification indicate that, in Norway, hay meadows originated during the Iron Age (500 BCE–1030 CE). This corresponds with the development of the iron scythe, a tool that facilitates mowing on a large scale.

Managed woodland

Dried leaves and twigs from broad-leaved trees were also used for winter fodder, especially elm, ash, and birch. Leafy twigs were cut in late summer when the leaves were still full of nutrients and knitted up in small bundles. The bundles were hung to dry in appropriate places and later transported to a barn or stored outside in special stacks. The most common method to harvest the trees was to make pollards; young trees were cut at appropriate height and the re-growth harvested about every fifth year (see CHARCOAL AND WOOD ANALYSIS).

For the harvest of leaf fodder, a special knife was developed in the Iron Age. However, in contrast to haymaking, which requires an iron scythe to be done efficiently, leafy twigs can easily be harvested using stone tools. Leaf harvesting is probably one of the oldest techniques of fodder collection for livestock. The antiquity and origin of the leaf fodder collecting is a classical question in palynology—for example, the cause of the elm decline detected all over northern Europe around 6,000 years ago which is now regarded to be a combination of elm disease and human impact. However, several local pollen diagrams from Norway show beyond any doubt the harvest of elm leaves from the Late Neolithic onwards. Probably other broadleaved trees were also harvested, but this is difficult to detect in the pollen diagrams as these trees produce flowers between each harvest, in contrast to elms that take longer to resume flowering following harvest. Although work is in progress, it is still a challenge to identify these woodlands in the pollen record (Bunting, Grant, and Waller 2016).

Coastal heathlands

Open coastal heathlands dominated by dwarf shrubs, mainly heather (*Calluna vulgaris*), developed from the special way coastal farming was adapted to the oceanic climate. Due to the Gulf Stream, the winters on the coast are much milder than elsewhere in Norway, with little or no snow cover. The farmers therefore let the small-stock live outdoors all year round. They survived the winters by eating heather and seaweed. In summertime they would also find grasses and forbs. Young heather is an evergreen plant; the nutrient content of the leaves is more or less the same during winter and summer. With access to sufficient areas of heathland in good condition, the animals had no problems surviving normal winters without any extra fodder. In order to maintain the fodder quality of the heather plants, the heathlands were regularly set on fire to rejuvenate the heather. This burning was always done during the winter in order to avoid damage to the roots and the seed bank in the soil. Each year, patches of heathland were burnt while others were left,

creating a mosaic of heather at different developmental stages, in addition to grasses and forbs.

From detailed studies, combining archaeology and palynology, it has been shown that there is a close connection between farming settlement, deforestation in surrounding landscapes, heathland development, and heather burning. The timing of heathland formation can vary both locally and among regions depending on farming conditions; several thousand years can separate the age of heathlands on two neighboring islands and also between regions: At Jæren, an area of early farming in southwest Norway, heathland formation started during the Neolithic, with most of the heathlands forming during the Bronze Age. In marginal farming areas along the coast north of Bergen, the Iron Age and early Medieval Age were more important periods. Both detailed and regional studies thus demonstrate that coastal heathlands in Norway have an anthropogenic origin.

Future directions

Although palynology is the main method used to gain information about vegetation development through time, interdisciplinary research is becoming increasingly important; close collaboration with archaeologists is needed to understand environmental management by livestock in earlier time periods, knowledge of the effects of different management regimes (e.g., type and number of grazing animals) on the vegetation is gained from ecological research, paleoethnobotany (see PALEOETHNOBOTANY) (plant macroremains from archaeological contexts) can elucidate the types of plants collected for fodder (see ENVIRONMENTAL ARCHAEOLOGY), and historical records bridge the gap between recent time and prehistory (Behre 1988; Birks et al. 1988; Krzywinski et al. 2009; Hjelle et al. 2012).

Palynological methods are also developing and several of these advances are important for research into environmental management with livestock. Modern analogs, that is, pollen surface samples from managed vegetation types (Krzywinski et al. 2009, 40, 201), have been shown to be useful in reconstructing past

land-use practices, and increased knowledge of the ecology of non-pollen palynomorphs (Schlütz and Shumilovskikh 2017) may make this proxy more widely used in the future. High-quality microscopes make higher pollen taxonomic resolution possible and may aid the determination of indicator taxa for different management regimes. Knowledge of pollen productivity in managed landscapes (Bunting et al. 2016) has become increasingly crucial as quantitative reconstruction methods have developed. A greater understanding of the size of the area reflected in a pollen sample is being developed (Sugita 2007); pollen diagrams from large and small sites reflect the vegetation differently and analysis of a number of sites can aid identification of the spatial extent of a habitat through time. On-going research in developing and improving quantitative reconstructions of past vegetation and landscapes (Gaillard et al. 2008; Sugita 2007; Bunting et al. 2016) has the potential to contribute to the understanding of the importance of environmental management with livestock in past societies.

SEE ALSO: Dating Pollen; Environmental Management with Fire; Osteology Vegetation Modeling Using Pollen Data

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Erosion

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The study of erosion has been a key topic in a wide range of archaeological research projects across the world for the last 50 years. Erosion is of global importance when discussing sustainable land use (past and present), human impact upon the landscape, landscape change, and the effect that erosion processes have had on the formation and preservation of the archaeological record. Erosion is the breaking down, movement, and deposition of soil and rock by the action of water, wind, or ice, which can be accelerated by seismic activity, climate change, and human action. In the process of erosion, the broken down material is moved from the place of weathering by a flowing agent such as water (hillwash or alluvial activity), ice in the form of glaciers, or by the wind. Mass movement, also known as mass wasting, is the movement of material down slope due to gravity in creeps, landslides, rock falls, and debris flows.

While studies focusing on erosion as a result of human impact have been undertaken across the globe, the Mediterranean landscape is a particularly useful case study because of its natural vulnerability to erosion resulting from a combination of its geological make-up, frequent tectonic activity (see *ARCHAEOSEISMOLOGY*), along with a semiarid climate that has seasonal variations in the amount and intensity of rainfall and the vegetation that this supports. These factors, coupled with a long and continuous occupational history, allows for the high-resolution study of the interaction of driving forces and rates and timings of periods of increased erosion.

Many of these Mediterranean studies have centered on the way in which hillslope processes have influenced the amount of sediment transported by water and gravity down slope and into river systems (see *RIVER SYSTEMS*). While on the one hand the movement of the soil is driven by climate, specifically seasonal distribution, quantity, and intensity of the rainfall, another

determining factor is the type of vegetation cover (dependent on the geology and soils that can support it). Vegetation can protect the soil and anchor it onto the slopes. Human modification of vegetation cover through clearance and land use (tillage and grazing) has been seen to have a direct effect on the amount of material eroded, that in turn increases the sediment load within alluvial systems. However there has been considerable debate about the relative importance of human influence on erosion rates.

One of the most significant pieces of research on Mediterranean erosion is Vita-Finzi's (1969) seminal publication, in which he identified two major phases of valley aggradation which he attributed to the last glacial period (Older Fill) (c.30,000–10,000 BP) and to Late Roman and medieval periods (Younger Fill) (AD 400–1850). Vita Finzi identified these two phases of alluviation in valleys across the Mediterranean and argued that they were the result of climatically driven erosion.

Vita Finzi's research has had a considerable influence on Mediterranean landscape studies, especially in landscape and regional archaeology as it served as the first long-term, large-scale developmental model which subsequent researchers have been able to compare to their own findings. It has also been at the root of an ongoing debate concerning the identification of triggers of increased erosion; that is, whether periods of increased erosion are climatically or anthropologically driven.

Mediterranean erosion studies have also been influenced in the 1990s by large European Union-funded projects which aimed to address modern concerns about increasing landscape degradation and desertification. MEDALUS (Mediterranean Desertification and Land Use), and the Archaeomedes project, incorporated an historical and at times archaeological component. MEDALUS set out to investigate and model the specific physical processes of desertification in the Mediterranean; viewing this as a result of long-term erosion derived from the interaction of extreme climatic events and intensification of land

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use in the historic period which tipped vulnerable landscapes past regenerative thresholds. The Archaeomedes project (1992–94) also sought to understand the process of landscape degradation and desertification, though from a more cultural perspective, and over a longer time period.

These projects made a direct link between land use and increased erosion in contemporary landscapes and were focused on defining the crucial thresholds beyond which the landscape could not regenerate (recover) and desertification took hold. This idea of “degradation” in the sense of loss of fertility and inability to regenerate entered academic language (see Butzer 2005 for a review) although critics of these projects, most notably Grove and Rackham (2001) took issue with the use of terms like “degradation” as unduly negative and have suggested that the role of the “human” element in erosion has been overstated.

A number of important geoarchaeological studies of landscape evolution that have taken place since the 1990s have stressed the dominant role of human management or mismanagement of land use practice which can be seen in the sedimentary record. The study of these landscapes has also been greatly enhanced by advances in fine resolution palaeoclimatic reconstructions based on several lines of environmental evidence (see PALEOENVIRONMENTAL RECONSTRUCTION). This palaeoclimatic evidence in conjunction with intensive small-scale valley studies has necessitated a reevaluation of the role of climate as increasing the vulnerability of a landscape to the effects of human disturbance (Bintliff 2000 and Butzer 2005 and references therein). Bintliff (2000) takes this further, stressing the impact of extreme climatic events on these already fragile landscapes.

Human modification of the landscape in the form of agricultural terracing is seen as an attempt to increase arable land by stabilizing steeper hillslopes, conserving pockets of arable soil and retaining as much rainwater as possible. Terraced landscapes reflect long-term investment of resources and energy, including preparation (leveling and clearance), cutting into the hillside and transportation of soil, as well as the building and maintenance of the terrace walls.

Studies of agricultural terraces have not only identified their antiquity (beginning in the Bronze Age (c. 3200–1500 BC) in many locales in Spain,

Italy, and Greece) and methods of construction, but also their role in landscape history. The dating and characterization of sequences of palaeosols and colluvial deposits that have accumulated after their construction provide insights into past land use as well as direct evidence of soil movement, offering high resolution data to establish the timing of erosion events (French and Whitelaw 1999; Krahtopoulou and Frederick 2008). The construction and maintenance of terraces can be seen as soil redistribution throughout the landscape in the short term instead of directly inhibiting soil loss over the long term (Bevan and Conolly 2011).

Terracing has often been cited as having an effect on valley fills. When they become abandoned or not maintained, their reservoir of captured soil is released down slope. Research on the island of Kythera has shown that after terrace abandonment, the main types of erosion are sheet wash (the removal of fine soil material overland by rainwater) and gully erosion (when slopes are sharply eroded by water that carries away exposed soil material) which on unconsolidated geology can greatly increase erosion of the slope and increase sediment flux within the local fluvial system (Krahtopoulou and Frederick 2008: 559–60). Recent work on historic agricultural terraces supports the findings of increased erosion after abandonment. It is clear, however, that terraces, just like the fills of alluvial systems, are complex and highly variable across the Mediterranean. The rate and extent of terrace degradation and subsequent erosion of the hill slope after their abandonment reflect the interactions of specific localized environmental factors (including geology and soil properties, topography and slope, the location of the terraces on the slope, and climate) and land use practices, terrace design, and maintenance.

Intensive archaeological survey in the Mediterranean has revealed an artifact-rich landscape, but the processes that created the abundance of archaeological evidence on the surface, particularly that from certain periods of history, are not fully understood. A recurrent theme in archaeological regional surveys has been to assess the “visibility” of the archaeological record on the surface, not only in terms of ground cover but also in terms of soil stability. Studies have attempted to compensate for differential visibility of material in terms of factoring in differences in

vegetation and geomorphology or have involved small-scale investigations on tillage and site disturbance. Erosion has been identified as a significant dynamic in the creation of the archaeological record, particularly in regions of the Mediterranean that are dominated by highlands and mountain ranges.

It should now be best practice for archaeological field surveys to include geoarchaeological analysis that assesses, among other things, the formation processes (see FORMATION PROCESSES) that have affected the presence of archaeological material on the surface. Central to this assessment is the examination of slope stability and an evaluation of the likelihood that material has either been disturbed or buried by past or more recent erosive processes. These investigations treat archaeological contexts, once they are enveloped within the soil matrix, as sediments, subject to the same physical processes. There are an increasing number of research projects that have undertaken regional erosion studies to enhance our understanding of the visibility and preservation of archaeological material (Ayala and Fitzjohn 2007). These investigations highlight the necessity of examining field-survey data in relation to the geomorphological development of a region, prior to interpreting the record as evidence of settlement patterns and regional history.

Geomorphological processes are considered a key factor in the preservation and visibility of archaeological surface finds across the landscape. With the adoption of geographical information systems GIS, the ability to model the erosive potential or risk that a landscape has been exposed to allows for the analysis of the complex relationship between ancient human strategies, geomorphic processes, and surface exposure of archaeological finds (Ayala and Fitzjohn 2007). Current developments of erosion models using GIS and other agent-based modeling software are not only used to reconstruct landscape evolution and predict rates of erosion but also, with the incorporation of historic and archaeological data, the land use choices and decision-making processes of past societies. While there is a tradition of geomorphological research into decision making and land use and land-cover change (LUCC) and the effects it has in erosion and patterns of landscape evolution (Wainwright and Millington 2010 and references therein) within

Mediterranean landscapes, it has only recently become part of the archaeological dialogue.

One of the most exciting potentials of this type of computational modeling is its ability to test different simulations of past land use choices as seen in the record of long-term environmental change. This active and dynamic way of testing different land use scenarios has been used in conjunction with surface survey results to analyze potential settlement and land use choices as well as isolating single management methods (i.e., terracing) and predict their original coverage and impact upon the landscape (Bevan and Conolly 2011). Exciting applications of agent-based models have also been created in an attempt to improve our understanding, or to support analysis of past societal interactions with the landscape and their potential impact on those landscapes.

SEE ALSO: Environmental Archaeology; Flooding; Geoarchaeology; Geomorphological Survey; Hydrological Modeling; River Systems

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Fish

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Fish have been consumed by people from the earliest times, as evidenced by both fish bones and fishing artifacts found at sites of human occupation. Shell fishhooks from Sakitari cave in Japan and the Jerimalai site in East Timor show that line fishing was practiced over 20,000 years ago, and at the latter site, tuna bones evidence fishing offshore as early as 42,000 BCE. At Blombos cave in South Africa, fish bones suggestive of inshore fishing have been identified in contexts dating from the Middle Paleolithic at 140,000–50,000 BCE, while in Europe evidence for fishing has been recovered from a number of Upper Paleolithic cave sites.

Although there are currently over 33,000 fish species, bones regularly recovered from archaeological contexts are usually from a fairly restricted range of taxa, with species exploited reflecting the available habitats (freshwater, estuarine, coastal, oceanic), resources, and technologies, fish behaviors (solitary, shoaling, pelagic, etc.), palatability, societal beliefs, and the economic strategies practiced by fishing communities.

Prior to industrialization and the development of deepsea fisheries (see DEEP-SEA FISHERIES), across the world most fish were captured in fairly shallow water using a variety of different nets and traps—often associated with fences or weirs, spears, harpoons, and leisters, gorges, hooks, and lines operated from the shoreline or from boats in coastal waters. There is a substantial literature documenting fishing prosecuted by coastal communities both historically and in the present day; Fenton (1997), for example, describes the many types of fishing practiced by the inhabitants of Orkney and Shetland over many centuries. Here, small inshore fish, predominantly saithe (*Pollachius virens*), provided not only protein but also oil, extracted by boiling the livers, which was

used as a crude lamp oil possibly from ancient times (Nicholson 2004).

Cut marks can indicate butchery methods, but it is possible to portion a fish without leaving discernible marks on the bones. The presence or absence of certain skeletal elements can also provide evidence for the preparation of fish for the table or techniques of fish preservation.

Fish that are seasonally abundant, such as salmon which migrate from the ocean to the upper reaches of rivers to spawn, have been fished throughout human history. Investigations into Pacific salmon fisheries by Campbell and Butler (2010) have shown the resilience of this fish to human exploitation over the last 7,500 years despite changes to both the ecological and social systems. European eels (*Anguilla anguilla*), which famously migrate from freshwater and estuaries to spawning grounds in the Sargasso Sea, have been the focus of major fisheries during both their migration downstream as silver eels and their migration upstream as elvers. During the medieval period in England they were so important that the Domesday Book and other medieval documents frequently record rents paid in eels, and weirs choked many rivers.

Apart from offshore, coastal, and riverine fishing, fish have been cultivated in ponds across the world and since at least the Roman period in Europe. Fish ponds were a common feature of royal and monastic estates in medieval times, when fish consumption accelerated as a response to urbanization and ecclesiastical edicts, since fish could be eaten on days when four-legged beasts could not. Some fish, including sturgeon and pike (*Esox lucius*), have been protected by royal ordinances and their remains, together with those of other large and expensive fish, can be considered markers of social status.

Fish remains can also provide evidence for trade, one obvious example of which is the trade in salted and fermented fish products around the Roman empire and beyond. Usually produced from fish blood and intestines or small oily fish such as sardines (*Sardina pilchardus*) and mackerel (Scombridae), fish sauces including

muria, *altec*, *liquamen*, and *garum* were popular condiments in the classical world. Evidence for the movement of these products, together with salted fish (*salsamenta*), is provided by distinctive collections of fish bones as well as written records and the amphorae used to store and transport them. Other techniques that have proven potential in this area include the analysis of aDNA (see ZOOARCHAEOLOGY AND ANCIENT DNA) and lipids (see ORGANIC RESIDUE ANALYSIS).

The interpretation of fish remains in paleoecological and paleoeconomic reconstruction is influenced by the ways in which the archaeological assemblage was created and recovered, as well as any taphonomic biases that may have modified it. While archaeological evidence for fish and fishing activities is largely through the identification of the remains of the fish themselves (bones, scales, otoliths) and inorganic fishing equipment (hooks, weights, weirs), both pre-depositional and post-depositional considerations affect their preservation (for examples see Wheeler and Jones 2009).

Fish bones vary in physical and chemical composition, with some, such as those of the cod family (Gadidae), being relatively large and robust for the size of fish, while cranial bones of salmon and trout (Salmonidae) are thin and fragile, particularly after spawning. Chondrichthyes (sharks, rays, and chimaeras) and Agnatha (hagfishes and lampreys) have skeletons made of cartilage. Only the teeth, dermal denticles (tooth-like structures in the skin), and calcified vertebral centra from sharks and rays are usually recovered archaeologically. The keratinous teeth of lampreys (Petromyzontiformes), attached to a sucker-like mouth in life, are a very rare find, although historically lampreys were a popular food.

Otoliths, distinctive calcium carbonate structures found in the inner ear, survive in alkaline environments, particularly shell middens. They vary in size between different fish taxa and some are much more readily identifiable than others. Scales vary in composition, structure, and size between different types of fish: some form bony plates (ganoid scales) such as the distinctive armour-plating of sturgeon (Acipenseridae), while cartilaginous fish have placoid scales (dermal denticles) and teleosts, or bony fish have leptooid scales which are either ctenoid (toothed

outer edge) or cycloid (circular). While dermal denticles and ganoid scales are fairly robust, ctenoid and ganoid scales are usually only found in waterlogged deposits or where mineralization has occurred, such as in cesspit fills.

Not all fish bones found on an archaeological site necessarily relate to human activity. Other mammals and birds also catch fish or scavenge their remains, and some animals, such as bears and otters, may be responsible for accumulations of fish bones in secluded places such as caves and chambered cairns. Natural fish mortalities also occur, such as the mass die-offs of Pacific salmon (*Oncorhynchus* spp.) after migration and spawning in fresh water.

Prior to the last decades of the twentieth century, most fish bones retrieved from archaeological excavations were recovered by hand. The assemblages so recovered usually almost entirely comprised bones from large fish and, consequently, earlier reports often present a very partial picture of the role of fish and fishing to communities and societies. Today, most excavations employ fine-mesh soil sieving as routine and thus a much wider range of fish bones are recovered, particularly of smaller individuals and species that were often the main target of coastal fisheries.

Identification of fish remains requires access to a comprehensive comparative collection. Although digital identification resources are becoming more common and there are a number of useful identification guides in print, these are best used to gain an overview of diversity and a guide to specific families or genera. Not all skeletal elements are equally diagnostic, and different approaches to identification have been advocated to suit the size of assemblages, diversity of fish found in various geographical locations, and the questions being asked (see discussion and references in Wheeler and Jones 2009, 149–153). The most easily identifiable bones are typically the jaw elements, but some fish have other diagnostic bones, such as the pharyngeal bones of cyprinids (Cyprinidae) and wrasses (Labridae), dermal scutes of sturgeons, and spines of stingray (*Dasyatis* sp.) and catfish (*Synodontis* sp./*Clarias* sp.).

Unlike other animals, fish grow throughout their life and so bone size may not be a useful indicator of species, although bone measurements

can be used to determine fish size if sufficient comparative material is available. Proxy measures used by fisheries researchers include size/age relationships and these can be reconstructed from measurements taken on modern and archaeological bones and otoliths, using allometric regression for species where the modern data have been collected. Incremental growth rings on scales, otoliths, and some bones can be studied to establish fish age and seasonality of capture, but considerable skill is required to accurately interpret the patterns and only extremely well-preserved material is suitable. Seasonality can also sometimes be inferred from knowledge of fish movements and ecology, particularly for migratory species.

Archaeological fish remains have much to offer fisheries science and conservation, providing time depth to investigations of population structures and movements beyond what can be gleaned from written historical records. Evidence of past fish distributions can contribute to a greater understanding of ecological change and aid fisheries management. Excavations at Coppergate, York (UK), revealed a change between the Roman period and the ninth century CE in the kinds of freshwater and anadromous fish recovered, from those found in clean, well-oxygenated water to taxa tolerant of mildly polluted water (Wheeler and Jones 2009, 136). Archaeological evidence for the historical distribution of burbot (*Lota lota*), now extinct in British rivers, can contribute to attempts to re-introduce this freshwater codfish, and archaeological evidence has been used to investigate spatial and temporal changes in the distribution of European eels (Kettle et al. 2008) and sturgeons (*Acipenser oxyrinchus* and *A. sturio*) in western Europe. Analysis of carbon and nitrogen stable isotopes extracted from archaeological fish bone collagen has proved to have considerable potential for identifying fish movements and zones of exploitation in marine and freshwater environments (Orton et al. 2011; Robson et al. 2016). Changes in oxygen isotope ratios within otoliths can be used to investigate changes in water quality and temperature, and, by extrapolation, season of capture.

The contribution of fish and other marine foods to the diet can be postulated both from a study of fish bone assemblages and from analysis of the stable isotopes of carbon, nitrogen, and

sulfur extracted from human bone collagen (see DIET AND CARBON ISOTOPES and DIET AND SULFUR ISOTOPES). A marked decrease in consumption of marine resources, including fish, in the early Neolithic across parts of northwestern Europe has been argued based on stable isotope data from human collagen, although the presence of coastal shell middens containing abundant fish bones particularly in Denmark indicates the likelihood of regional variation (Richards and Schulting 2006). High values of nitrogen and sulfur isotopes have been linked to the consumption of freshwater fish (Nehlich et al. 2011).

With the adoption of these biomolecular techniques, fish and fishing as topics of archaeological enquiry have undergone something of a renaissance, including closer engagement with fisheries science and conservation. While proteomics (ZooMS) and aDNA analyses offer great potential for species identification, they are unlikely to replace more traditional methods, due to cost and availability of equipment. However, these new avenues of research offer exciting opportunities for archaeoichthyologists to engage not only with the past but also with the future.

SEE ALSO: Diet and Nitrogen Isotopes;
Zooarchaeology and Stable Isotopes

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Flooding

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Flooding occurs when areas of ordinarily dry land are inundated by water from the sea, from inland water bodies such as rivers (see RIVER SYSTEMS) and lakes (see LAKE DEPOSITS), or as a result of surface water run-off. Flooding has influenced (and continues to do so) patterns of human occupation and activity (see INHABITED LANDSCAPES), as well as the formation and preservation of archaeological sites (see FORMATION PROCESSES AND TAPHONOMY). Contemporary flooding impacts the conservation of archaeological deposits and sites, historic buildings and structures, posing challenges for their ongoing preservation. Actions taken to adapt to contemporary and future flood risks, such as construction of flood defenses, can have an impact upon archaeological deposits and affect historic structures, but also present an opportunity to investigate archaeological sites and historic places and learn from past adaptations to flooding.

Identifying evidence of flooding in the archaeological record requires frameworks that incorporate geoarchaeological (see GEOARCHAEOLOGY) and geomorphological (see GEOMORPHOLOGICAL SURVEY) methods to characterize the deposits. Floodplain muds are typical of fluvial flooding in temperate climates, these resulting from finer-grained sediment associated with slower moving or slack flood waters and settling over a wide area. Seasonal or episodic flooding may be indicated by soil development as flood waters dry out. In contrast, deposits associated with flooding from glacial outwash or more high-energy water inundation will be poorly sorted and may include much larger irregular clasts. Paleoenvironmental approaches (see PALEOENVIRONMENTAL RECONSTRUCTION) can help to reconstruct the environmental context for floods, including seasonality and frequency, but the taphonomy of the paleoenvironmental remains themselves can be affected

by the flood processes—for example, in admixing remains from wider contexts. This reworking of material by flood waters and other fluvial processes poses a particular challenge for Pleistocene archaeologists where artifacts and faunal remains frequently occur in disturbed or reworked contexts. Identifying marine inundation, whether as a consequence of transgression (sea-level rise; see SEA-LEVEL CHANGE) or storm surge, tidal surge, or tsunami, is undertaken in a similar way and presents similar challenges. Fauna, including molluscs (see MARINE MOLLUSCS and LAND AND FRESHWATER MOLLUSCS), foraminifera (see FORAMINIFERA), ostracods (see OSTRACODS AND CLADOCERANS), and diatoms (see DIATOMS) can be used to help distinguish between deposits derived from marine or freshwater ingress.

In many instances, investigation of the wider landscape and seascape context will be needed to fully understand the nature, extent, and impact of any flooding event. Geophysical survey may help to map even deeply stratified or submerged deposits, and coring (see CORING), micromorphology (see MICROMORPHOLOGY), and hydrological modeling (see HYDROLOGICAL MODELING) can all contribute. Where significant accumulation of flood deposits has occurred in the past this may obscure earlier archaeology, not just to the passing observer but also sometimes from archaeological prospecting techniques such as field walking, traditional geophysics (e.g., see MAGNETOMETRY and REMOTE SENSING), aerial survey (see AERIAL PHOTOGRAPHY), and light detection and ranging (LiDAR) (see LIDAR DATA VISUALIZATION AND PROCESSING). Investigation of currently flooded landscapes such as those beneath contemporary seas and lakes will require specialist investigation and excavation approaches (e.g., see MARINE EXCAVATION). One such area is Doggerland; today it is an area of seabed in the North Sea, between Britain, Denmark, Germany, and the Netherlands, but 12,000 years ago it was dry land connecting Britain to mainland Europe. Five-thousand years later it had completely vanished beneath the North Sea, a consequence of a series of inundations associated

with sea-level rise. Multidisciplinary research has begun to reveal this lost landscape and its associated archaeology (e.g., Coles 1998; Gaffney et al. 2017).

Seasonal flooding was often welcomed by past societies who made use of the predictable irrigation and rich sediment associated with flood waters. In areas with a monsoon climate (where a seasonal change in winds brings a sudden change in precipitation), such as east and Southeast Asia, the seasonal flooding can be particularly dramatic. It has been proposed that a shift in the monsoon that decreased precipitation contributed to the de-urbanization of the Indus Valley around 4,000 years ago, and similar suggestions have been made for the demise of Neolithic culture in central China around 4,500 years ago (e.g., Wenxiang and Liu 2004). Seasonal flooding of the Nile (in summer) was so important to the people living along its banks because of the rich sediment that the flood waters brought that “nilometers” (Figure 1, right) were constructed in Pharaonic Egypt to measure the depth of flood waters and determine taxation levels according to the harvests that might be predicted (a high flood would mean better crops and higher taxes).

Harnessing flood waters for irrigation and the nutrient-rich deposits is an activity replicated in many parts of the world, sometimes by artificially flooding areas of land (see RICE). Water meadows, once common to many areas of low-land England and elsewhere in Europe, are an

example of deliberate flooding of the landscape to improve pasture for grazing. Initially this was achieved by temporarily blocking a watercourse and causing it to overflow onto adjacent land (known as “floating upwards”), but later (from the seventeenth century onwards) this developed into sophisticated systems of sluices and channels that afforded better control and avoided harmful waterlogging (Smith and Stamper 2013).

Seawater is a less welcome intrusion for agriculture, although salt marsh has been used for grazing for centuries. More importantly, coastal areas, in particular where seawater ingress can be controlled, have been a focus for the production of salt often for millennia. Archaeological remains and deposits associated with salt production are frequent in many coastal areas; for instance, the “Red Hill” archaeological deposits found in coastal areas of eastern England are the result of prehistoric salt production.

Flooding is not always welcome and there is archaeological evidence for construction of flood defenses in Roman Britain (Jecock 2011) showing that, while the rivers and coast were attractive areas to settle, due to the transport links and other services they afforded, they also presented challenges. In North America, increases in flooding of the Mississippi have been correlated with the decline of occupation at Cahokia in the thirteenth and fourteenth centuries CE (Munoz et al. 2015). As well as being potentially destructive, flood waters can harbor diseases; for instance,



Figure 1 (Left) Flooding at East Lyng and Athelney, Somerset, England, showing the early medieval burh, causeway, and monastic complex as islands in the flooded landscape. Source: Photo D. Grady, copyright Historic England, published with permission. (Right) Rawda nilometer, Cairo. Source: Copyright John Cooper, published with permission.

the World Health Organization recognizes that malaria epidemics in the wake of flooding are not uncommon. Osteoarchaeological studies (see PALEOPATHOLOGY) have revealed evidence for malaria as a significant disease in medieval Europe in areas prone to flooding. Interestingly, the study of incidence of schistosomiasis (a condition caused by parasites associated with still water) in Egyptian archaeological populations suggests that it was the transition from reliance solely upon the natural flooding of the Nile to controlled irrigation techniques that contributed to the increase in prevalence of the condition (Hibbs et al. 2011).

Outburst floods are sudden flooding events resulting from the sudden failure of a barrier (natural, such as a glacial moraine; volcanic barrier; or human-constructed barriers, such as dams), usually of a lake or sea, resulting in a very sudden release of a huge volume of water. Such events suddenly and catastrophically change the landscape and are sometimes referred to as “mega floods.” Marine flooding is often of this type, particularly when it occurs as a result of storm surge (such as the catastrophic flood that affected the North Sea in 1953, killing thousands of people in the Netherlands, Britain, and Belgium), seismic activity (as suggested for the Bronze Age caldera-creating eruption of Santorini in Greece), or overwhelming of natural barriers. It is suggested that the breaching of the Dover Straits between what is now southeast England and northern France was the result of one such “mega flood” when the glacial lake in the area of the North Sea broke through a narrow chalk ridge, possibly as the result of an earthquake (Gupta et al. 2017). In recent history, such events have been associated with dam failures, although in the eighteenth century, catastrophic breach of a landslide barrier that had been created by earthquake on the Dadu River in Sechuan, China days earlier led to flooding over thousands of miles and the death of over 100,000 people (Dai et al. 2005).

Tsunamis are waves caused by a sudden displacement of water in a large water body, usually an ocean or lake, most often as a result of tectonic activity. The resulting waves can be extremely large and have a terrible impact, often causing widespread devastation and death far in land—as seen in the Boxing Day tsunami that hit the Indian Ocean in 2004. The word tsunami comes from

the Japanese for “harbor wave” and they have been particularly associated with Japan, with the islands having experienced a number of the most significant tsunamis of the past few hundred years (Enshunada Sea 1498, Ise Bay 1586, Nankaido 1707, Ryuku Islands 1771, Sanriku 1896, North Pacific Coast 2011, all predominantly affecting Japan and featured in the “Top ten most destructive Tsunamis in history” in *Australian Geographic* 2011). Researchers investigating a sea cave in Aceh, Indonesia have identified a depositional sequence providing a record of tsunamis stretching back 7,400 years—the most complete record of tsunami deposits ever recorded that has the potential to inform understanding of the impact of these events upon the inhabitants of the islands, and potentially further afield (Rubin et al. 2017).

There are references to significant floods in the myths and legends of several societies (e.g., Noah in the Middle East, Gilgamesh in Mesopotamia, the Sumerian King List, Manu and Matsya in India). The common references to floods in the Judaic, Sumerian, and Babylonian stories have led some to speculate that there may have been a catastrophic flood in the region that is the origin of all these stories. However, although archaeological evidence shows that flooding was a significant part of life in ancient Mesopotamia, there is no evidence to suggest a single region-wide catastrophic flood; “flood deposits” found at Ur by Sir Charles Leonard Woolley in the early twentieth century are not replicated at other sites in the region. The “Black Sea deluge,” the proposed catastrophic flooding of the Black Sea in the sixth millennium BCE, is also a source of controversy, not over whether the area was inundated with seawater from the Mediterranean (researchers agree that this did occur) but about whether the changes observed in the deposits were the result of gradual or sudden one-off flooding.

In some places, it may not be flood stories but place names that point to a flooded past. For instance, in England, names with “ey” on the end, such as Athelney and Romsey, denote an island (from the Old English *ēg*); indeed, Athelney lived up to its name in the severe flooding experienced in Somerset, England in winter 2013–14 when the settlement was visible as an island in the flood waters (Figure 1, left).

In many areas, the incidence of contemporary flooding is set to increase as the impacts of global climate change are felt and sea levels rise. This poses a challenge to the conservation of archaeological remains and historic structures that may be at an increased risk from flood-related damage such as erosion and water damage. In 2017, intense rains and flooding in Peru threatened to harm a number of archaeological sites and monuments, and similar concerns have been raised elsewhere. Coastal flooding is frequently associated with high-energy events, such as storm surge or tsunami, and is therefore often accompanied by other processes, such as erosion, that can also cause harm to archaeological sites and historic structures. In Britain, storm surge wave impacts have been responsible for some dramatic discoveries, including Skara Brae (Orkney, Scotland) which was revealed as a consequence of storm-related coastal erosion but is threatened by future inundation from similar events. Marine incursions also have an impact upon groundwater levels—increasing them as the lighter freshwater is pushed up by the heavier seawater to mean sea level and above. Therefore, as sea levels rise, low-lying coastal areas can become freshwater wetlands with brackish (water with higher salinity than freshwater but lower than seawater) areas around estuaries. Recognizing and understanding this in the archaeological record can help to interpret archaeological sites and past human activity that exploited the rich resources associated with such areas; however, it also affects the contemporary and future preservational context of archaeological sites.

Adapting to these changes in sea level and flooding risk presents a challenge. Constructing flood barriers to hold flood water back (or slow it down) is one approach; however, this can impact upon archaeological deposits and historic places, which might be disturbed or altered in the process. Another approach is to adapt buildings to the risk of flooding so that when they flood they can quickly recover. In this regard, traditional building techniques and materials (such as the use of lime mortars and plaster, solid timber, and stone) have been shown to be far more resilient and recover more quickly than many modern materials. In fact, we can learn from buildings such as the Bishops Palace

at Wells, England, which we know from historical records was constructed in the thirteenth century as resilient to frequent flooding. There is also an increasing interest in “natural” flood management techniques which involve working with natural processes or traditional land management practices to slow down the movement of water and decrease run-off. These techniques are most successful where consideration has been given to the history of the catchment and human activity associated with it.

Industrial archaeology particularly that related to water control and use and infrastructure can be threatened by flooding. There have been instances where historic bridges have been blamed for exacerbating flooding by restricting the flow of water, and even instances where historic bridges have been redesigned and rebuilt to alleviate this (e.g., Charminster, southwest England). Some concerns have been raised about the possible impact of modern flooding in areas with an industrial heritage that might release harmful materials (such as lead and zinc) into the water and wider landscape (see WATER POLLUTION). There has been particular consideration of this in historic industrial areas of England and Wales (e.g., Howard, Kincey, and Carey 2015).

SEE ALSO: Augering; Marine Excavation; Palynology

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Foraminifera

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Foraminifera are single-celled organisms (protists) that possess a hard test (shell) and preserve in the sedimentary record after death. This test is secreted by the cell and is mainly composed of agglutinated walls (detrital grains glued together with organic cement) or calcium carbonate (predominantly calcite). The test consists of a number of chambers that arrange in numerous shapes and sizes. Adult foraminifera range in size from less than 0.40 mm (planktonic forms) to up to 10 cm in width (larger benthic foraminifera). They are tolerant to a range of variables such as salinity, temperature, oxygenation, and organic and nutrient flux. Foraminifera are exclusively marine; most are benthic (living on or under the seabed) although a few genera are planktonic (floating in the water column). Foraminifera are among the most abundant and ubiquitous shelled organisms in marine environments. Their distribution ranges from the intertidal salt-marshes to the deepest ocean trenches and from the equator to the poles. They respond rapidly to environmental changes, and individual species indicate specific environments. For example, a strong relationship exists between the altitudinal distribution of modern benthic foraminiferal species and tidal levels. Transfer functions that quantify this relationship have provided a basis for the reconstruction of Holocene changes in sea level (see SEA-LEVEL CHANGE) at a very high resolution. These reconstructions are constrained by taphonomic factors such as reworking and differential dissolution, resulting in mixed assemblages, indicated by poor preservation and unusual assemblage structure.

Foraminifera represent several advantages in comparison to macrofaunal fossils (e.g., molluscs). For example, they present a higher density in marine sediments, and consequently much smaller sediment volumes are needed for a reliable assessment. They commonly have shorter

life cycles and populations therefore respond quickly to environmental changes. After reproduction or death a large part of the foraminiferal assemblage is preserved in the sediment.

Foraminifera can be extracted from sediments obtained from surface samples and cores (sample size of at least 50 cm³). Samples should be washed through sieves (minimum 63-μm mesh) to retain sand-sized grains and this residue dried. The retained foraminifera can be picked out by hand with the aid of a binocular microscope using reflected light (target number of 300 specimens). When large numbers of sand grains are present, foraminiferal tests can be concentrated using a heavy liquid, with the tests being floated off (Murray 2006). Identifications are based on type collections, descriptions, and photographs in foraminiferal manuals, which can also be obtained through online resources such as the World Register of Marine Species (www.marinespecies.org).

Benthic foraminifera have important archaeological applications. For example, as common microscopic components of many ceramics, they represent a potential tool for determining the provenance of archaeological ceramics and raw materials involved in ceramic production, as well as the reconstruction of ancient ceramic technology (Quinn and Day 2007). Thin sections represent the most convenient means of detecting their presence in ceramics. Biostratigraphical and/or paleoenvironmental interpretations of foraminiferal assemblages in archaeological ceramics provide a reliable means of determining the source of the raw materials used in their manufacture. Detailed knowledge of local and regional geology is a crucial part of all provenance investigations of archaeological ceramics. Furthermore, foraminifera have the potential to contribute to the understanding of ceramic technology. The presence of foraminifera of conflicting geological ages or environmental tolerances is interpreted as evidence for both clay mixing and the addition of temper. Ancient ceramics containing well-preserved foraminifera are considered to have been low-fired, and

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samples with poorly preserved foraminiferal assemblages are assumed to have been subjected to a higher degree of firing.

Rosendahl, Ulm, and Weisler (2007) developed techniques of foraminiferal analysis to distinguish between natural and cultural marine shell deposits in coastal areas. Cheniers and beach ridges are natural shell deposits formed by oceanic processes above the mean high tide level. They contain a wide range of taxa representing all shell size ranges, from juvenile to adult, and often large quantities of fragmented shells, reflecting the composition of the source areas. In contrast, shell middens are accumulations of shells that have been selected from the environment by humans as food (see MARINE MOLLUSCS) and are therefore indicative of cultural processes. These large concentrations of shells date from about 8–7 ka onwards, although earlier deposits have been found in some coastal caves. However, different natural processes and anthropogenic activities can produce the vertical and horizontal mixing of both types of shell deposits. Foraminiferal density can be used to differentiate natural and cultural shell deposits, as they abound in natural deposits formed by marine processes (>1,000 tests/100 g of sediment), whereas foraminifera are rare (<50 tests/100 g of sediment) or absent in deposits formed primarily by shellfish collection.

Sea levels have been substantially lower than the present for most of human existence throughout the Quaternary. Since 18 ka BP, glacio-eustatic sea-level rise of 120 m has transgressed important shelf and coastal areas of the world, submerging numerous Paleolithic and Mesolithic sites. Several of the world's religions describe a legendary Great Flood in their literature, such as the story of Noah's Flood in the Judeo-Christian tradition. A few years ago, this biblical narrative was connected to the Black Sea area. Two different scenarios were proposed: an Early Holocene event caused by a catastrophic Mediterranean inflow at 8.4 ka BP that accompanied the Laurentide Ice Sheet collapse, and an earlier Late Pleistocene event brought on by Caspian influx between 17 and 14 ka BP after the Late Glacial Maximum. In both scenarios, rising post-glacial water abruptly filled the Black Sea and submerged the previously exposed shelf. Accordingly, early Neolithic farmers were flooded and forced to

move into the interior of Europe, carrying with them knowledge of farming as well as the memory of the deluge. Yanko-Hombach, Gilbert, and Dolukhanov (2007), using paleoenvironmental reconstructions (see PALEOENVIRONMENTAL RECONSTRUCTION) based on foraminiferal content from numerous sediment cores, together with other paleontological and archaeological evidence, found that the Late Pleistocene inundation was more substantial. However, there was no evidence to support any catastrophic submergence of prehistoric Black Sea settlements. Similar scientific methodologies have been applied in other areas of the world to study landscapes submerged by the post-glacial rising of sea level, for example Doggerland in the North Sea.

Ancient harbors and their natural surroundings contain rich geoarchaeological records, with information on human occupation and use of the environment, natural catastrophes (e.g., tsunami impacts), and regional tectonic activity. Coastal systems are characterized by a general sedimentary progradation since 7 ka BP, at the end of the Holocene marine transgression. High-resolution sampling of excavated sections and cores (see SAMPLING IN ENVIRONMENTAL STUDIES) allows a very precise reconstruction of coastal and harbor history using the temporal and spatial distribution of foraminifera. Foraminiferal geoarchaeological studies began in the 1990s at Caesarea Maritima, eastern Mediterranean, to investigate its harbor's Roman history (Reinhardt, Patterson, and Schröder-Adams 1994). Later, Marriner and Morhange (2007) observed a remarkable repetition in ancient harbor stratigraphy (the Ancient Harbor Parasequence), in terms of both its facies and temporal constraints, evidenced through the use of paleontological indicators, notably foraminifera and ostracods (see OSTRACODS AND CLADOCERANS). Modification of microfossil assemblages were caused by local anthropogenic activities and human use of the harbor basin as a waste depocenter over thousands of years (Irabien, Cearreta, and Urteaga 2012). Among the numerous ancient harbors characterized by distinctive foraminiferal assemblages, Portus (near Rome) is remarkable because it is partially buried beneath thick tracts of coastal and fluvial sediments related to the Tiber delta progradation (Di Bella et al. 2011).

SEE ALSO: Characterization of Ceramics;
Geoarchaeology

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Formation Processes

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Although some archaeological remains, notably artifact scatters and standing buildings, are found at the land surface, the majority are below ground, where cultural material deposited at or near the surface has then been buried. The term “formation processes” is widely used in archaeology to cover both the behavioral aspects of archaeological deposition and the natural or seminatural processes involved in burial and taphonomy. The behavioral aspects are covered elsewhere (see *BEHAVIORAL ARCHAEOLOGY*); this entry discusses how sites are buried, followed by the soil and groundwater processes by which they are disturbed or transformed.

Burial agents and processes

Water

Flowing water both erodes archaeological stratigraphy and buries it, sometimes both. Alluvial sites in wetter climates are often associated with paleochannels and well-preserved waterlogged material (see *Groundwater conditions* below), while those in semi-arid environments are characterized by high-energy rearrangement and rapid burial (Schiffer 1987). Erosion at coastal and shoreline sites can be extreme, but this also presents opportunities for exposure and excavation. Lake- and sea-level changes lead to very good preservation by rapid sediment covering, protection, and waterlogging. However, significant rises in sea level (see *SEA-LEVEL CHANGE*), especially the approximately 120 m post-glacial rise of the last 20,000 years, must have put large amounts of archaeological remains beyond current practical reach.

Wind

Wind can act as both an erosive and a depositional agent in a similar way to water. Suspended particles, entrained by high-velocity winds, act to sandblast upstanding structures in arid and semi-arid environments. The particles come to rest where the wind drops and deposits are therefore sorted by grain size. Loess is the name given to the silt-sized (grains of 2–63 μm) deposits, which, although occurring in deserts, are most widespread in periglacial areas, forming a northern hemisphere mid-latitude belt from China, through Europe, to the United States. Cover sands, sheet sand, or dunes are windblown sand (grains typically $>63 \mu\text{m}$) and are more characteristic of deserts, but localized deposits do occur in periglacial conditions.

Animals

Animal hooves can transport large amounts of soil when herds are driven over suitable surfaces. In addition, the dung and bedding of stabled animals will leave thick deposits where ashed (as in many Mediterranean caves) or preserved by desiccation. Some colluvium may also have animal origins, resulting from trampling action on slopes, but the major animal processes are disturbance rather than primary burial (see below).

Humans

Deliberate dumping of soil, building of earthworks, mining waste, manuring, and rubbish scattering are primary anthropogenic burial processes. Humans also collect, discard, and burn materials at or near habitation sites, producing waste dumps, shell middens, and ash mounds. Secondary site burial processes occur when earth is used as a construction material and then decays in situ. Topsoil has long been a construction material in North Atlantic cultures, and the use of adobe (see *ADOBE*) is widespread in the arid areas of the Americas. One of the most

striking examples of this process is the repeated mud-brick house collapse which forms tells in the Middle East.

Volcanoes

Ash, pumice, and lava can all bury archaeological sites and will often form datable layers between horizons in areas of regular eruption. Air-borne ash can travel long distances depending on wind conditions, but the most extreme events are pyroclastic flows, in which a fast-moving dense cloud of hot ash engulfs areas extending many miles from the original eruption site. These are the volcanic materials that buried Pompeii and Herculaneum in 79 CE.

Gravity

Natural rockfalls bury habitation sites near cliff faces and contribute to most cave sediments (see CAVES AND FISSURES). Colluvial accumulations are attributable to gravity (see EROSION) but will typically require human activity (e.g., deforestation) or climatic change (e.g., aridification) to promote the instability needed to produce substantial downslope movement. Large episodic accumulations are characteristic of the Mediterranean valleys (see Limbrey 1975).

Post-burial disturbance agents and processes

Animals

Numerous macro- to mesoscale organisms disturb the burial environment. Rabbits, badgers, gophers, packrats, prairie dogs, and foxes are all renowned for their burrowing activities, while ants, termites, and earthworms deposit fine material at the surface, causing some stratigraphic deflation and making finds sink into the soil (Canti 2003).

Plants

Rooting activity moves objects in the soil, but its effects are generally small. Tree throw by wind or human action is, however, an extremely

disruptive force whereby large root plates potentially enclosing well-preserved stratigraphy are lifted to a position partially above the ground surface, then rot away, re-depositing it in a new stratigraphic position.

Humans

Plowing and other forms of tillage cause massive disruption of archaeological stratigraphy where new ground is being broken. Thereafter, in situations of repeat cultivation, compaction from machinery wheels can lead to breakage of weaker objects such as ceramics and some bones (see Oxford Archaeology/Cranfield University 2010). Cultivation on slopes renews destruction by slowly lowering the land surface, bringing deeply buried material closer to the surface.

Ice

Freeze-thaw action on archaeological sediments causes numerous periglacial phenomena (cryoturbation), as well as disruption and patterning of finds. Flake dispersal experiments by Bowers, Bonnicksen, and Hoch (1983) in Central Alaska, for example, suggested that needle-ice and frost-heave combine to produce dispersal that could mimic human activity. Examples of archaeological stratigraphy being disturbed in this way are rare, however, probably because of the unsuitable conditions for habitation and a tendency for site destruction in periglacial environments (see GLACIAL AND PERIGLACIAL ENVIRONMENTS). Cryoturbation's major effect is to cause difficulties of stratigraphic interpretation when excavators are unfamiliar with the features it produces, such as the fine subsoil partitions associated with patterned ground in many northern European sites.

Post-burial chemical transformations

Once buried, sites and their artifacts undergo transformations dependent on the chemical make-up of the burial matrix, the ambient temperature, and the groundwater conditions. Ceramic and metallic objects are only mildly affected by these differences, with metals tending

to produce corrosion products that protect or engulf them under a range of environmental conditions. By contrast, preservation of biological materials and artifacts made from them (except where charred) is very much influenced by the burial conditions. At sites with extreme dryness or cold, and sites where the burial medium is unfavorable to life (e.g., the Halstatt salt mines), processes are slowed to a point where change is minimal over human or even millennial timescales and biological materials are frozen, pickled, or mummified. These conditions are either rare or poorly explored, and most archaeological sites are undergoing slow transformation by a complex interplay of chemical and physical changes.

Chemical make-up

The primary mineral make-up of the burial medium is key to any understanding of formation processes. Soil material formed chiefly of silica (sands, silts, some clays, and some volcanic ashes) tends to produce acidic (low pH) conditions when subjected to evapotranspiration surplus (where precipitation exceeds evaporation from the surface). The other main mineral components that commonly make up the bulk of the burial medium are calcium compounds—notably carbonate (limestone) and sometimes sulfate (gypsum), both of which are alkaline (high pH).

In acidic conditions, all the alkaline archaeological materials tend to dissolve, so calcium carbonate (most shells and shell artifacts) and calcium phosphate (a major component of bones and bone artifacts (see *BONES AND IVORY*)) will disappear. Preservation of organic materials such as wood and leather is usually better in acidic conditions, but other factors (particularly groundwater conditions; see below) may be more important.

Organic matter is the other major component of burial environments. It is mildly acidic in nature, but has little impact on pH by itself; it does, however, provide the fuel for microbially driven reduction processes (see *Groundwater conditions* below) which can result in strong acidification.

Temperature

Even at 50 cm down from the surface, mean annual soil temperature can be in the mid-20s (°C) in some tropical regions or down to below 0°C in periglacial areas. This range has a profound effect on the rate of transformations, but not the trajectory.

Groundwater conditions

In well-drained sites, where the groundwater table is below the archaeological remains, water from rainfall events is rapidly lost and the soil atmosphere returns quickly to oxygenated conditions. Under these circumstances, organic materials are rapidly decayed, and alkaline matter such as calcium carbonate (limestones and many shells), sulfate (gypsum), and phosphate (bone mineral material) are all slowly dissolved. Other compounds including calcium phosphate and calcium carbonate will sometimes precipitate under waterlogged conditions, and can impregnate or replace organic materials.

If, however, the drainage is locally impeded, gases move much more slowly through the soil and reduction can start to build up quite rapidly. Aerobic soil organisms which normally produce CO₂ from the breakdown of organic material can no longer thrive and are replaced by organisms producing methane (CH₄). This change slows the breakdown of organic matter and thus promotes preservation of some artifacts such as wood, textiles, and leather. In reduced soils, another important feature is that iron (Fe) compounds go into solution, accompanied by a change from the red or rust colors of Fe III (insoluble) compounds to the blues and greens of soluble Fe II. Brown and reddish sediments will therefore go blue or green and either lose their iron staining or have it redistributed as mottles and iron pans when drainage (and thus oxidation) is re-established. This is the process responsible for the iron deposition and associated drainage impedance in the South Scandinavian barrows (Holst, Breuning-Madsen, and Rasmussen 2001).

If a source of sulfate (SO₄ salts) is present in waterlogged sites, commonly as a result of seawater incursion at coastal locations, then a particular group of specialized microorganisms can metabolize the oxygen from the sulfate. This

process leaves reduced sulfur available in the soil water, and either hydrogen sulfide (H_2S) gas or pyrite (FeS_2) is created. The gas will disappear by diffusion out to the atmosphere, but pyrite can remain in the soil indefinitely or until oxygenated conditions are re-established. At this point, the pyrite oxidizes to sulfuric acid and iron oxides, producing very strong acidity which can be devastating for archaeological remains (see, for example, the destruction at Starr Carr recorded by Milner et al. 2011). In calcareous areas, the sulfuric acid will neutralize soil calcium carbonate, in which case gypsum (CaSO_4) is formed.

Process interactions

Processes have been discussed here in an ordered sequence of three phases. Clearly, however, real site histories can go through multiple iterations or have simultaneous processes ongoing at any one time. A site may be partially buried, waterlogged, dried out again, and reworked by soil organisms, then eroded or re-buried. Formation processes tend to repeat or remain the same in stable geomorphic or climatic situations, but the older the site is, the more processes can have operated as environments changed over the longer term.

SEE ALSO: Desert Environments; Diagenesis of Bone; Flooding; Geoarchaeology; Lake Deposits; Peat Deposits; River Systems; Taphonomy

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FURTHER READINGS

Fruits, Vegetables, and Nuts

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Definitions

From a botanical point of view a fruit can be defined as the ripened seed-bearing ovary (simple fruit) or ovaries from one or more flowers (aggregate and multiple fruits, respectively) of a flowering plant, although in some cases it also includes nonovarian tissue (accessory fruits, such as apples and strawberries). In this context, “nut” is a type of fruit (simple dry indehiscent) that does not open after ripening, retaining its seeds. Hazelnut and acorn are examples of botanically defined nuts, but almond, for instance, does not belong to this category and is classified instead as a type of fruit called “drupe”.

A “vegetable,” on the other hand, is a broader categorization that usually refers to all plants that include edible parts, although it commonly refers to their nonflowering parts, such as roots, tubers, stems, leaves, and buds. In culinary and cultural terms, however, the distinction between fruits, vegetables, and nuts is rather more abstract. Usually the sweeter edible fruit plants that can be eaten as a snack but are not normally part of the main meal are classified as fruits, whereas those that are more savory in taste are considered vegetables. Tomatoes and cucumbers, for instance, although technically fruits, in practice are thought of as vegetables. Similarly, whereas black pepper is a fruit in botanical terms, it is classified as a spice (see SPICES). In this framework, the term “nut” commonly refers to edible kernels that are enclosed in a hard shell. As food and taste are culturally subjective, definitions and approaches to such edible plants in the past would have varied both spatially and temporally. Acknowledging this potential bias, their definition adopted here will follow the modern cultural approach, while their study in archaeology needs

to take into consideration the context of their recovery in order to allow insights into their use and, thus, classification.

Recovery

The study of fruits, vegetables, and nuts in archaeology is traditionally part of the field of paleoethnobotany (see PALEOETHNOBOTANY), while palynology (see PALYNOLOGY), phytolith, charcoal, and wood analysis (see PHYTOLITH ANALYSIS and CHARCOAL AND WOOD ANALYSIS) can also add significant information on the presence, use, and management of these plants. Although certain parts of these plants, like the stones of some fruits and the shells of nuts, are large enough that they can be retrieved by the naked eye at archaeological sites, the recovery of macroremains of fruits, vegetables, and nuts in greater numbers and their systematic study can only be achieved by taking soil samples (see SAMPLING IN ENVIRONMENTAL STUDIES). Water-sieving and flotation are the most common recovery techniques used for the treatment of soil samples. In very arid areas, dry-sieving suffices for the separation of such plant remains from normally sandy contexts.

Preservation: cultural and taphonomic considerations

Seeds and other plant parts can be preserved in archaeological contexts under special conditions, most commonly in waterlogged (anoxic), very dry (anhydritic), or frozen environments, as carbonized through incomplete burning, and by mineral replacement of the organic parts when in contact with diluted minerals (see FORMATION PROCESSES). Mineral replacement is also common in species that generate mineral deposits resistant to decomposition, such as hackberry fruits that produce carbonates in their pericarp. In temperate and Mediterranean climates where waterlogging and carbonization (in the case of the latter) are the two major

forms of preservation, fruits and vegetables are predominantly preserved in waterlogged conditions, whereas nuts are commonly found in both preservation modes (e.g., Jacomet 2013).

This bias in the preservation of fruits and vegetables is the outcome of a series of both cultural and taphonomic factors. Fruit flesh and the edible part of vegetables, which are composed mostly of various soft tissues, do not preserve well under charring, and when they do, their identification is very difficult due to their usually fragmented nature and the general lack of diagnostic features (but see Hather 1993). Notably, vegetables are usually ready for harvest and consumption before setting seed, and it is these seeds that tend to be more readily preserved and easier to identify. In addition, fruits and vegetables do not normally come into contact with fire as part of their processing and preparation for consumption, reducing their chance of being preserved by carbonization. Nuts, on the other hand, can be roasted and their shells have few uses other than possibly fuel, so they are more likely to be burnt, thus increasing their chance of surviving as carbonized remains.

In arid, desert environments, fruits, vegetables, and nuts preserve very well, often retaining some of their original color, if somewhat darker and more brownish. An increase in the study of desiccated macroscopic plant assemblages, mostly from North Africa, has provided a glimpse of the breadth of material preserved and the impressive range of fruits and vegetables, among other food plants, used. Detailed paleoethnobotanical investigations—for instance at the two most important Roman trade ports on the Red Sea coast of Egypt, Berenike (e.g., Cappers 2006) and Myos Hormos, also a port in the Islamic period (Van der Veen 2011)—have revealed a lengthy list of food plants. In both settlements, fruits were the most numerous food plant group, highlighting the variety they added to the diet and their importance also as traded items.

Contextual biases and research questions

The contexts and sites in which fruits, vegetables, and nuts are usually found are dictated to a certain extent by their predominant preservation mode, which in turn impacts on the type of research

questions that can be addressed. Waterlogged preservation requires a high-water table and/or deep stratigraphy, which are usually encountered in long-lived settlements. Thus, good representation of fruits and vegetables occurs at certain site types, such as towns (see URBAN ENVIRONMENTS), and in particular parts of the world, such as in northern and central Europe. An interpretational issue posed by waterlogged (but also very dry) contexts that needs to be considered relates to whether the food resources, such as fruits and vegetables, have been deliberately deposited or form part of the natural vegetation. This is the case, for instance, for wild fruits, like various berries common across Europe that could grow as ruderals within and around settlements and are often found within paleoethnobotanical samples. In areas where sites lack deep features or where the archaeology lies above the permanent water table, for example at many rural sites, plant remains are found mostly in a carbonized state, and fruits and vegetables are normally underrepresented.

Mineral-replaced plant macroremains are mostly recovered from human fecal deposits, such as cesspits and garderobes, with fruits being among the most common such finds. In historic urban sites, such contexts are often associated with houses of the higher social class, providing a better understanding of the vegetative food sources of the wealthier part of the population.

The investigation of issues like food consumption and trade, dietary breadth, and arboriculture and horticulture thus needs to take into account all the potential biases in each preservation mode.

Origins, domestication, and use

Fruits, vegetables, and nuts have been important food resources, following the human trajectory since its very beginning. They have also been used for the production of beverages (e.g., wine), oils (e.g., sesame and olive oil), dyes (e.g., from beetroots and onions), even containers (e.g., gourds), for medicinal purposes, and as fodder, craft, and construction material. Gathered from the local environments, several of these plants became increasingly managed by humans, some eventually being fully domesticated, whereas others remained wild resources, at least until

recently. Acorns gathered from the wild, for instance, were one of the staple resources in many parts of the northern hemisphere, such as in California where archaeological evidence attests to the long time-depth of their use (Pearman 2005, 133–134). Ethnobotanical work has also provided some interesting insights into the complex nature of the relationship between hunter-gatherers and the vegetative world and the management of fruit and vegetable staples by these people. For instance, a traditionally major food source for many Aboriginal groups in Australia were yams, which although not domesticated were carefully managed. This was achieved by preserving certain sections in the areas in which the plant grew for future exploitation and by harvesting the plants in such a way as to remove the tuber but not the top part with the growing vine, ensuring production in the following seasons (Hynes and Chase 1982).

The origin of fruit, vegetable, and nut domesticates can be traced across different parts of the world, and for many still remains a matter of enquiry. Southeast Asia is a key region from which a great number of domesticated fruit species originated, such as banana and various citrus fruits. Olive (see OLIVES AND OLIVE OIL), grape (see GRAPES AND VITICULTURE), fig, and date palm formed the basis for the development of horticulture in the Mediterranean basin, with the first two occupying a central part in debates regarding, for example, the emergence of Aegean palatial societies. Apples and pears originated in temperate central Asia and similarly wild plum and walnut are thought to be native in temperate Eurasia. The most important fruits of African origin are watermelon and melon. The Americas, on the other hand, have contributed some key staple foods, such as the potato and tomato, which have shaped national cuisines and influenced socioeconomic changes around the world. Such an example is large-scale migration and social restructuring as a result of the potato blight disease in Ireland in the nineteenth century.

The domestication process of fruits, vegetables, and nuts is often very complex and the subject of on-going research that affords new insights into the socioeconomic networks of the people and cultures involved. Distinguishing wild from domesticated varieties, which provides valuable information for the early history of such plants, is often particularly difficult, and requires a

cross-disciplinary approach, with genetic studies and the increasing application of geometric morphometric analysis of archaeological and modern specimens proving particularly fruitful. Horticulture and arboriculture appeared in many parts of the world much later than agriculture, partly due to the higher financial and longer-term labor investment, and the more advanced techniques and tools needed for the cultivation of some of these species (see OLIVES AND OLIVE OIL). In Europe, the voyages of discovery and the emergence of “scientific” botanical gardens during the seventeenth and eighteenth centuries contributed significantly to the movement and emergence of numerous new varieties of fruits, vegetables, and nuts. Nowadays, the expansion of monocultures and the general reliance on a few genotypes of each species renders them more susceptible to disease and adverse climatic conditions. Research on these plants aimed at a better understanding of their “biography” is thus crucial not only for an in-depth appreciation of the interactions of people with their environment through time, but also for the development of improved varieties and sustainable use.

SEE ALSO: Archaeology; Beverages; Desert Environments; Domestication; Environmental Archaeology; Lake Deposits; Oils and Fibers; Potatoes; Taphonomy

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Glacial and Periglacial Environments

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Introduction

Climates over the last 2.6 million years (during the Pleistocene or Quaternary) have fluctuated markedly and these shifts have resulted in periods of ice increase and decrease at mid to high latitudes and in the mountains. In high-latitude regions, this has resulted in shifts between colder episodes (glacials), during which ice cover may increase, and warmer episodes (interglacials), with reduced ice cover. Within the cooler episodes, periods in which ice sheets and mountain glaciers expand (glaciation) tend to be relatively short (although they do have a significant impact on the associated landscapes). Much of the time during these cooler episodes is characterized by lower temperatures, reduced sea levels, and altered vegetation patterns, but with little or no glaciation except in upland areas. In many respects, these conditions represent the “norm” between the extremes of the glaciated landscape and the short-lived interglacial episodes.

The term glacial is derived from the Latin “*glacialis*” meaning cold or frozen; the term periglacial refers to an area adjacent to a glacier or ice sheet subject to repeated freezing and thawing. This term was coined by the Walery von Lozinski, a Polish geologist, in the early twentieth century. Today the term is used to refer to nonglacial processes and features of cold climates (André 2009) that may or may not occur in proximity to glacial ice.

Glacial environments

The expansion of ice through mountain regions as glaciers and across lowland areas as ice sheets has left a distinct suite of features for geologists and geomorphologists to decipher. These vary from erosional features such as striations on rock (Figure 1a) and ice-molded bedrock (such as stoss-and-lee forms and roches moutonnées) to depositional features such as till (Figure 1b) moraines (debris from melting ice), eskers, and drumlins (linear or mound-shaped deposits of sand and gravel deposited during glaciation). Generally, processes associated with glacial environments are detrimental to the preservation of archaeological remains and no evidence is currently available to indicate that humans were active in such extreme environments until, perhaps, the Holocene.

Glacial environments and glacial activity have been important in changing landscape structure and modifying features of the pre-glacial environment. For example, a catastrophic collapse of a pro-glacial lake in the southern North Sea during Marine Isotope Stage (MIS) 12 times eroded a major channel through the chalk downland connecting southern England with northern France (see FLOODING). This process created the English Channel and resulted in Britain becoming an island in the subsequent interglacial when sea levels attained levels close to those experienced today (Gupta et al. 2017). This glacial activity also blocked the course of the River Thames into East Anglia and diverted it southwards into its modern channel (Gibbard 1985), creating the modern geography of southern England.

Glacial activity has been responsible for the burial and preservation of some important geological and archaeological sequences. For example, around the Norfolk coast in eastern

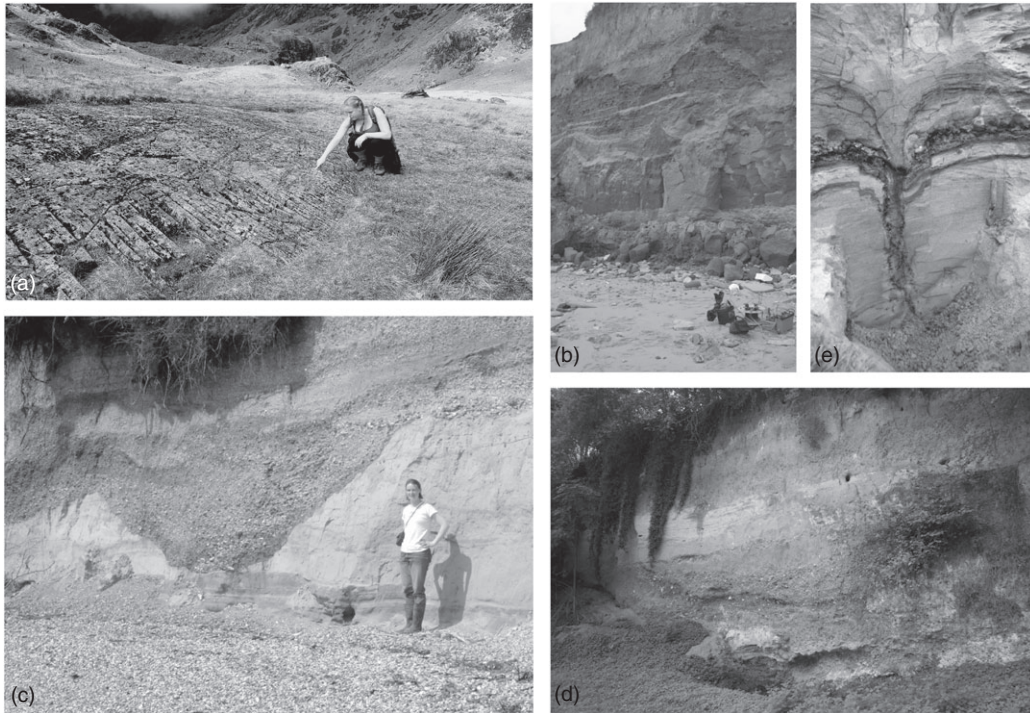


Figure 1 (a) Ice-striated rock surface near Llyn-y-Gadair, Cader Idris. (b) Till deposited by ice at Happisburgh, Norfolk during the Anglian glaciation of eastern England. (c) Coarse-grained gravels deposited by braided channels during cold climate conditions at Stanswood Bay, Hampshire. (d) Complex cold-stage deposits at Cagny-la-Garenne, Somme valley. Loessic sediments are present at the top of the profile and are underlain by soliflucted gravels. (e) Ice wedge cast from Covehithe, Suffolk.

England, glaciation in MIS 12 buried the important Cromer Forest Bed sediments that contain not only important faunal and floral records of Middle Pleistocene environments but also the tools and footprints left behind by northwest Europe's earliest occupants (Ashton et al. 2014).

Periglacial environments

The term periglacial environment is used here in its broadest form and encompasses a wide range of climatic conditions, ranging from the earliest evidence of global cooling following an interglacial, through to full glacial conditions. In northwest Europe these conditions result in a range of different environments developing. They are associated with lowered sea levels (see *SEA-LEVEL CHANGE*), river systems (see *RIVER SYSTEMS*) transporting coarse-grade

sediments (Figure 1c), vegetation shifted towards grassland-dominated ecosystems, and faunas associated with herd-dominated species such as reindeer, horse, and mammoth. Permafrost (deeply frozen ground) may characterize parts of the cooler climate cycle. Reconstructing these environments has been possible because of a wide range of environmental indicators (beetles, molluscs, small mammals, and plant remains) which are often preserved within fluvial or lacustrine sediments associated with these landscapes.

A range of sediment types and geological structures provide scientists with evidence for these cooler conditions. Sediments include the wind-blown loess found extensively in northwest Europe (Figure 1d) as well as across large parts of Eurasia. Milder climatic episodes within these cool episodes may be indicated by the presence of paleosols within the loess (Figure 1d). Sediments characteristic of seasonal melting of

permafrost include solifluction deposits (debris flows of typically unsorted sediments downslope during spring melts (Figure 1d)). Features developed within sedimentary units may also be indicative of frozen ground conditions in the past, for example, ice wedges (Figure 1e). Other depositional systems also attest to cooler conditions. River systems tend to carry coarser loads (Figure 1c) during spring and summer thaws while occupying the multiple channels of a braided channel system.

Archaeologically, periglacial landscapes are important as environments in which Paleolithic populations, at least as far back as the Middle Paleolithic, once thrived (Pettitt and White 2012). Climate cooling associated with these cooler events that resulted in the expansion of ice sheets and lowering of sea levels opened large areas of the continental shelf to colonization by plants and animals (Gaffney, Fitch, and Smith 2009). These landscapes are known to have been used by humans, including Neanderthals (Tizzard, Bicket, and De Loecker 2015), during the Middle Pleistocene. Elsewhere, sediments deposited under periglacial conditions, such as the sands and gravels of the major river systems, contain rich archives of stone tools swept from the occupied landscapes into the rivers. These records form rich archives for Paleolithic archaeologists (White 2016).

SEE ALSO: Erosion; Formation Processes; Paleoenvironmental Reconstruction; Temperate Environments

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Grapes and Viticulture

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Grapes, the fruit of the grapevine *Vitis vinifera*, have been consumed by human societies in Europe, the Mediterranean, and western Asia since ancient times, either freshly harvested or transformed through the course of time into various forms of food and drink, as well as medicines (e.g., Galen's medicinal wines), perfumes, and ointments (see **PERFUMES AND COSMETICS**). Originally distributed in its wild form in areas spreading from the Caspian Sea to the western Mediterranean (Terral et al. 2010), cultivation introduced the grapevine to many parts of the world. Wine, the produce *par excellence* associated with grapes and viticulture, due to its mind-altering properties (see **DRUGS AND PSYCHOTROPICS**), would have generated sensory experiences enhancing the mnemonic power of the event, be it rituals and festivals among Bronze Age Hittite elites, symposia and religious festivals honoring Dionysus in ancient Greece, wedding feasts such as that of Cana, or "brainstorming" among officials of ancient Persia, reported by Herodotus. Such occasions could have enhanced a sense of belonging or underlined social distinctions. More mundane uses of wine include the ancient Greek breakfast (cereal rusks soaked in wine ἀκράτισμα), culinary uses in sophisticated recipes recorded by Athenaeus, and wine served in Roman (*popinae*) and Byzantine taverns.

Wine holds a significant position in archaeological discourse on social stratification, elite emergence, feasting, and trade. Textual and pictorial evidence underlines the luxury nature of wine among Bronze Age societies. Wine has often been considered a key factor in the emergence of Bronze Age elites, among the Sumerians, Egyptians, Minoans, and Mycenaeans in the Near East and the Aegean (McGovern, Fleming, and Katz 1995) (see **BEVERAGES**). In other parts of Europe, to the north and northwest,

during the Iron Age (approximately 800–450 BCE), wine, together with serving and drinking paraphernalia, seems to be a means of elite distinction among beer-consuming cultures, with impressive finds unearthed at sites such as the princely burials at Hochdorf and Vix (Dietler 1996). Seen from the wine-consuming countries' perspective, beer, on the few occasions it is mentioned in the literature, was regarded as the "barley wine" of foreigners. Archaeological science offers various means of detecting and pinpointing the origins of grapevine cultivation and wine making, methods that have evolved over the years opening up an array of potential for future explorations.

Paleoethnobotany (see **PALEOETHNOBOTANY**) offers direct evidence for the use of grapes: remains of grape pips, stalks, and fruit have been unearthed from archaeological habitation deposits under waterlogged, charred, mineralized preservation conditions (see **FORMATION PROCESSES**). Although sporadic finds of grape pips form poor evidence for grape consumption, large quantities of pips and/or pips with grape skin, known as grape pressings, and whole fruits, corresponding in most cases to raisins, leave no doubt for the systematic harvesting of grapes and their drying for later consumption of the fruit or their pressing for the extraction of grape juice. Early grape pressings are known from a burnt Neolithic house at Dikili Tash in northern Greece dated to 4300 BCE (Valamoti et al. 2007), while whole raisins are reported from an Early Bronze Age (2900 BCE) room at Tell es-Sa'idiyeh in the Jordan valley (Cartwright 2003). Experimental archaeology (see **EXPERIMENT IN ARCHAEOLOGY**) has contributed significantly towards the distinction of the different grape products in the paleoethnobotanical record and the distinction between wild and domesticated pips (Cartwright 2003; Smith and Jones 1990).

The mere presence of grape finds in the archaeological record does not suffice to suggest cultivation and domestication (see **DOMESTICATION**), as grapes can be harvested from wild female plants. Remains of *V. vinifera* charcoal (see **CHARCOAL**

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AND WOOD ANALYSIS) could suggest pruning and therefore cultivation of the grapevine, detected around the 3rd millennium BCE in western Asia (Miller 2008). The palynological record (see PALYNOLOGY) offers an additional analytical tool in the quest for ancient viticulture: the appearance or increase in *Vitis* pollen in long sequences provides strong indications for grapevine cultivation (Bottema and Woldring 1990).

Paleoethnobotany provides a means to recognize grapevine domestication, and therefore cultivation in the archaeological record, on the basis of grape pip measurements. Typical domesticated grapevine characteristics include elongated pips with long stalks and a greater length to breadth ratio, based on observations on modern pips (Mangafa and Kotsakis 1996). Inferring the timing of viticulture is, however, a difficult task, as some cultivated varieties possess morphologically wild pips. Wild-looking pips dominate Neolithic finds; nevertheless, recent morphometrics show that well into the historical period, when systematic viticulture is known from textual evidence, wild-looking pips continue to be present in the paleoethnobotanical assemblages (Terral et al. 2010). Grapevine cultivation involved the vegetative reproduction of grapevines selected for color, aroma, and/or sweetness of the grapes, a process culminating in special wines of the ancient world such as Greek Thasian and Roman Falerian wines, an early form of “denomination of *origin*.” Early attempts to manage the plant and select for and propagate particular individuals led to viticulture that was geared towards increasingly large production levels, well beyond the potential of wild plants and usually associated with wine production.

The paleoethnobotanical record shows that despite earlier inferences for a single origin of viticulture, in the Caucasus or the Near East, multiple origins in the wider area of the plant’s natural distribution are a more likely scenario, rooted already in the Neolithic (Valamoti et al. 2007). This insight is supported by modern and ancient DNA studies of grape pips (Manen et al. 2003) and morphometrics (Terral et al. 2010) which show variability in ancient grape populations corresponding to different varieties. It is also in agreement with the multiple mythological origins of the ancient Greek wine-god Dionysus,

including Phrygia in the Near East, the Aegean, Boeotia, and Thrace.

The archaeological identification of ancient wine making is closely connected to discussions related to the origin of viticulture. Yet, viticulture is not a prerequisite for wine making. Early wine making in the archaeological record can be inferred through paleoethnobotanical remains (pressings of grapes indicating juice extraction) and residue analysis (see ORGANIC RESIDUE ANALYSIS) of pots potentially intended for wine. These methods have enabled the detection of tartaric acid/tartrate, succinic, malic, and citric acids on sherds from sixth century BCE Lattara (gas chromatography–mass spectrometry (GC-MS), ultra-high performance liquid chromatography (UHPLC) coupled with tandem MS, UHPLC-MS/MS; McGovern et al. 2013); maldivin (LC-MS) on sherds from Areni-1 Cave (4000 BCE) in southeast Armenia (Barnard et al. 2011); and tartaric, malic, syringic, and succinic acids from sherds from a Neolithic house interior at Dikili Tash (4300 BCE; Garnier and Valamoti 2016), to mention but a few. Besides wine, grape juice (must) could have had other culinary uses—for example, for the preparation of vinegar, a reliable preservative in antiquity, or of a condensed grape syrup, known as *ἐψημα* and *sapa* in the Greco-Roman world, still surviving in modern Turkey and Greece (*pekmez*, *πετιμέζι*). Unfortunately, such alternative preparations, also containing tartaric acid, are largely ignored in interpretations of residue analyses and wider discussions of early wine making, with few exceptions (e.g., Valamoti et al. 2007; Barnard et al. 2011).

Pottery provenance studies, including ceramic thin sections (see CHARACTERIZATION OF CERAMICS) combined with numerous finds of wine amphorae and seals unearthed across the Mediterranean offer further archaeological evidence for viticulture, wine production, and wine importation to nonproducing territories. The colonization of the western Mediterranean by the Greeks and Phoenicians was a trigger leading to the introduction of viticulture and wine making in the western Mediterranean around the sixth century BCE. Thus, from the cradle of viticulture in western Asia and the eastern Mediterranean, the cultivation of the grapevine not only spread westwards, but also took off in these new lands

in later times, with French wines, not Greek or Levantine, holding a worldwide reputation nowadays. The Romans spread viticulture further through their conquests, while the eastwards spread of the grapevine to China appears to have taken place around 2,400–2,000 years BP, evidenced by paleoethnobotanical finds from funerary contexts at Shengjindian, Xinjiang, and Yanghai (Jiang et al. 2015).

Archaeological science, through the combination of paleoethnobotany, morphometrics, ancient DNA studies, ceramic residue analysis, and pottery thin sections, has made considerable steps towards the investigation of grapevine exploitation in the Ancient world, from prehistory to later periods, as well as of the circulation of wine through ceramic thin sections in antiquity as well as in later times. Future paths of investigation include further elaboration of the methods employed for detecting ancient wine, a better understanding of the evolution of domestication, and the development of different varieties through a combined use of morphometrics, experimentation, and broadening of the paleoethnobotanical datasets investigated. An integrative approach combining archaeological science with artifactual evidence and archaeological context, as well as textual sources, compared with similar data over large spatiotemporal scales, hold the key to revealing regional patterns in food choices related to grapes and wine in the ancient world.

SEE ALSO: Chemistry in Archaeology; Fruits, Vegetables, and Nuts; Gas Chromatography–Mass Spectrometry (GC-MS); Taphonomy

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Hydrological Modeling

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Most archaeological research eventually leads to a consideration of water supply for the ephemeral, seasonal, or permanent camps and settlements. Therefore, integrated hydrological research and concepts are becoming increasingly important for better understanding of past societies.

Archaeological investigation of hydraulic structures may provide data not only about horizontal and vertical stratigraphy, construction techniques, function, and use, but also about the date of features and how different occupation sites relate to each other. Whole systems can better be understood through comparative study, taking into account that interregional migration and exchange networks would have involved the transfer of hydrological and hydraulic competencies. Often hydraulic engineering was focused not only on supplying drinking water but also on more sophisticated and pleasurable aims such as providing water for fountains, water gardens, bathhouses, and the like. Such systems were often developed to improve public hygiene and living conditions as well as for entertainment.

Understanding water supply and water catchments in arid environments is particularly important, as in these regions water availability is often a limiting factor, affecting both seasonally and permanently occupied sites. Water scarcity becomes even more important when we consider the high variability of water resources in the desert margins of arid lands which is highly dependent on climatic preconditions.

Generally, and from a technical perspective, hydrological modeling in archaeological context, that is, archaeohydrology, aims to reconstruct human/cultural water utilization and drainage in the past. It may relate to tangible spheres, for example archaeological findings of specific hydrologic catchment area, or it can deal with

past human behavior or with water resources in general. In scientific terms, archaeohydrology provides quantified data about water resources and their use, and analyzes or identifies different types of water management strategies, taking social structures and economic parameters of archaeology into account (Wellbrock, Grottker, and Gebel 2017).

Archaeohydrological research involves the application of a whole range of different methods including archaeology/cultural anthropology, archaeobiology, geoarchaeology (see GEOARCHAEOLOGY), geomorphology (see GEOMORPHOLOGICAL SURVEY), and environmental sciences, including hydrology. From a hydrological point of view, archaeohydrological research should follow a three-stage process or agenda: identification, quantification, and utilization. Of course, these aspects need not follow a strict sequence, with different parameters playing a recursive and iterative role in the various contexts of analysis.

Archaeohydrology has strong links to paleohydrology, which aims to reconstruct past channel patterns, river floodplain, alluvial chronology, and so on (Gregory and Benito 2003; Baker 2014). The main difference between these disciplines is that paleohydrology focuses on the natural environment and archaeohydrology considers artificial and technical measures and how those manipulate the natural water cycle. Also there are strong links with geoarchaeology, geomorphological and sedimentological research (reconstruction of cultural and natural landscapes, and land use), and biological research (e.g., palynology (see PALYNOLOGY), paleoethnobotany (see PALEOETHNOBOTANY), zooarchaeology (see ZOOARCHAEOLOGY), physical anthropology, and the various isotope analyses).

As a first step in an archaeohydrological investigation, if possible all water resources should be identified for the location being investigated. In addition to surface runoff, groundwater is often the basis of water supply for ephemeral, seasonal, or permanent occupations. In particular in arid to semi-arid environments, the type of

water resources present and the probability of their combined use have a major influence on the reliability and availability of water. Remote sensing (see AIRBORNE REMOTE SENSING) and meteorological data as well as topographical and geological maps are prerequisites in helping to identify local water resources. Next, a preliminary interpretation of hydraulic installations at each site will help to identify the type of water resource used. Geophysical prospection, that is, mainly electrical resistivity tomography (see ELECTRICAL RESISTIVITY), may provide information about local hydrogeology and the abundance of shallow aquifers. As well as such technical or scientific information, archaeological evidence is useful for revealing functional aspects of water use in the past local environment. Even reference to the environmental knowledge of present-day inhabitants may provide valuable information for the interpretation of past environments, and water resources and their utilization.

Once the different types of water resources have been identified, hydrological models can provide quantitative data on the amount of water available perennially, seasonally, ephemerally, spatially, and so on. The types of models used can be manifold. In general, these comprise both surface runoff models and groundwater models. Water balance models, which consider equilibrium between water demand and supply, can also be useful. If necessary and possible, a combination of different models should be employed. The range of models applied in this step may vary from very simple empirical ones to more detailed numerical models. The type of model depends on the site/location/region itself and on the question posed.

For the calibration of any hydrological model, data are needed that represent the local/regional preconditions. Principally, in-field measurements of parameters such as infiltration capacity and groundwater recharge are necessary. Additionally, remote sensing data (elevation, meteorological data, etc.), geological data (type and spatial distribution of aquifers and aquifuges), and topographic data (land use, land cover, vegetation) are required (Harrower 2010). This calibration is the most difficult part of the modeling process.

Water sampling to determine the main ions and isotopes present may be helpful for evaluating sources of water as well (Leibundgut, Maloszewski, and Külls 2009). Such investigations may indicate if (fossil) aquifers are laterally fed by shallow aquifers or interflow (e.g., in wadi beds). Therefore, this type of analysis can assess water reliability. Moreover, dissolved carbon dioxide can be used for radiocarbon dating (see RADIOCARBON CALIBRATION AND AGE ESTIMATION; Leibundgut et al. 2009). If aquifers are accurately located, near-surface long-term water-level monitoring can be useful to ascertain seasonal and spatial water abundance as well as allowing for calibration of groundwater models. The combination of calibrated hydrological models with proxy-data and paleohydrological and paleoenvironmental reconstruction (see PALEOENVIRONMENTAL RECONSTRUCTION) is also possible.

Finally, the interpretation and functional reconstruction of hydraulic installations (e.g., canals, dams, wells, cisterns, troughs) can provide a more profound understanding of water use. Therefore, this step is essential in interpreting the hydraulic installations found during archaeological excavations or surveys. Moreover, the approach should aim to both reconstruct the water management system as a whole and interpret single features or findings.

In addition to archaeological excavation, geophysical prospection, including magnometry (see MAGNETOMETRY) and surveys using ground-penetrating radar (see GROUND-PENETRATING RADAR) can be helpful for the reconstruction of whole systems. This is especially the case when geophysical findings are verified through ground-truthing. The mapping of any surface remains related to the system to be reconstructed is also necessary, and topographical survey is essential for determining drainage patterns and directions of water flow.

Single features or whole systems can be represented by technical models usually linked to methods of hydraulic engineering. For instance, the flow capacity of a canal can be estimated by simple empirical equations, for example, if there are markers indicating water levels. Such markers may consist of calcareous sinter deposits which

are formed due to turbulences when carbon dioxide is degassed from the water. Sinter deposits themselves may provide data about operation times and water sources (Sürmelihiindi et al. 2013). Diatom assemblages (see DIATOMS) may indicate velocity or depth of flow, general flow conditions (flowing or standing water), and even the water quality.

If the system to be reconstructed is more complex, numerical models are necessary. Such models may comprise two-dimensional water-level simulations for different operation modes. The output of such models will help in understanding the general layout of the system and the water management strategies employed, and finally foster ideas regarding overall water resource management.

For the reconstruction of horticultural or agricultural regimes, a plant–water–soil model is helpful. Such models not only consider the amount of water needed by the plants, but also take meteorological data (precipitation, evaporation) and soil properties (field capacity, grain size distribution, and thickness of several layers) into account. The outcome of such modeling may suggest a potential schedule of irrigation as well as help quantify the amount of water needed to sustain the regime. Generally, modeling plant–water–soil interaction will help to clarify which operation mode is possible or most likely.

Of course, for reconstructing horticultural systems we need to know which type of plants were grown, since they have major impact on the local water balance and therefore on the amount of water needed. Thus, such research has strong links with geoarchaeology and paleoethnobotany (see PALEOETHNOBOTANY) (Engel et al. 2012). Pollen or phytolith analyses (see PHYTOLITH ANALYSIS) can also help to identify plant remains in the sedimentary environments being studied. Geomorphological methods provide data about soil genesis and environmental factors, and are useful as proxy-data for paleoclimate and paleohydrology. Furthermore, dating sequences by means of conventional radiocarbon dating (see RADIOCARBON CALIBRATION AND AGE ESTIMATION) or optical stimulated luminescence (OSL) (see DATING AND OPTICALLY STIMULATED LUMINESCENCE) help to set up local chronologies for horticultural

practices and the technical systems used at sites.

Aside from functional information, the reconstruction of water supply and management regimes can tell us about water consumption by humans, plants, and livestock, as well as provide information on hygiene, leisure pursuits, and human behavior and how all these are interlinked with—or help the interpretation of—anthropological findings and data.

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Lake Deposits

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Paleolimnology is the study of lake sediments to obtain a long-term perspective on environmental change. The intellectual roots of paleolimnology extend to numerous disciplines with diverse aims. Given its ability to shed light on human–environment interactions, paleolimnology offers a powerful addition to archaeological research that cannot be fully realized by solely examining ancient artifacts or cultural remains. The blending of these two fields of study is a natural fit as paleolimnology can track the presence and impact of ancient societies on local environments, as well as reconstruct past climatic conditions or other environmental changes that may have contributed to cultural expansion or collapse.

Archaeologists have incorporated lake sediment studies into their research, even during the formative years of paleolimnology. For example, Patrick (1938) examined diatoms (see DIATOMS) from an archaeological excavation site in New Mexico containing the remains of mammoths and other megafauna. Changes in diatom assemblages from varying layers over time reflected changing salinity conditions, which corroborated changes recorded in faunal remains.

Despite the potential of lake sediment research to archaeology remained largely underutilized for many decades. This began to change during the late-1960s when researchers started shifting their focus from reconstructing cultural histories to considering the wider cultural landscape and the environmental factors influencing the rise and fall of early societies. This new research direction, commonly referred to as the “ecological approach,” also occurred at a time of advancements in paleolimnological methods, particularly in coring techniques (see CORING) and determining accurate sediment chronologies. It was during this time that the partnership of

archaeology and paleolimnology within projects became more common.

Tracking ecological impacts

The early applications of paleolimnology to archaeological studies typically focused on tracking the impacts of earlier societies on the environment. For example, Cowgill and Hutchinson (1964) analyzed the sediments of Lago di Monterosi near Rome to document the activities of the Roman Empire in this region. Using chemical analyses of the sediment profile, they showed that the Romans cleared the shores of the lake and frequently burned vegetation in a likely effort to prevent ambush from a road that ran adjacent to the lake.

In the Canadian Arctic, researchers used paleolimnological approaches to document how whaling activities of Thule Inuit nearly 800 years ago altered aquatic conditions and left distinct biological and biogeochemical signatures in pond sediments (Douglas et al. 2004). The Thule culture (ca. 1200–1600 CE), which preceded the Historic Inuit, were skilled maritime hunters and capable of killing bowhead whales from large skin-covered boats. The nutrients released from slaughtered whale carcasses enriched nearby oligotrophic ponds, which resulted in marked ecological changes including shifts in the species composition of diatom algae and the enhanced growth of aquatic mosses. Coincident with the ecological changes, the pond sediments record an enrichment in stable isotopes of nitrogen ($\delta^{15}\text{N}$), a proxy often used to track marine-derived nutrients as $\delta^{15}\text{N}$ is enriched in higher trophic levels (such as whales and seals). This study documented the earliest form of “cultural eutrophication” from Canada and the United States.

Tracking past cultural activities

Among the most common proxies used in paleolimnology to track human presence are pollen and charcoal from agricultural activities. One

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of archaeology's long-standing mysteries is what happened to the Rapa Nui on Easter Island. Although there is still no consensus on what caused sociopolitical changes on the island, sediment core data provide valuable paleoenvironmental information on human–environment interactions. Pioneering lake sediment research by Flenley et al. (1991) indicated that, prior to human arrival, the island was forested or at least partly forested. The dominance of *Palmae* pollen in the sediment core, dating back prior to human arrival, indicates a forest dominated by palms, which is in stark contrast to the grassland ecosystem found on the island today. Charcoal horizons in sediment cores provide the timing for burning and initial forest clearance by Polynesian farmers, which began around 1000–1200 CE. Around this same time, there is evidence for increased soil erosion, and pollen data suggest that herbaceous species began to replace the initial palm-dominated forests, although forest clearing did not occur at the exact same time and rate in different parts of the island. Anthropogenic burning is widely considered the main reason for deforestation of the island (Rull et al. 2013); however, climate-related factors such as droughts have also been suggested as a factor in deforestation.

Pollution signals archived in lake sediments are another method that can be used to track past human activities (see WATER POLLUTION). For example, in South America, archaeological investigations surrounding the history of metallurgy have been hampered by extensive looting of metal artifacts. Analyses of metals (Ag, Bi, Pb, Sb, and Sn) in a sediment core recovered from a lake adjacent to the largest silver deposit in the Bolivian tin belt reveal that precious metal smelting in southern Bolivia occurred several centuries earlier than previously believed (Abbot and Wolfe 2003). Elevated metal concentrations in the sediment core dating to the early eleventh century CE suggest that scarcity of pre-Incan silver artifacts is not due to a limited ability to locate, extract, and refine silver ores. Rather, any artifacts from this time period were likely looted or recycled and transported elsewhere both before and after contact by Europeans. The metal pollution signal in the lake sediments thus provided evidence for a major pre-Incan silver industry, which would have otherwise remained

unknown due to the scarcity of metal artifacts from this time period.

Directly measuring human presence

Sediment cores can also contain microartifacts, or remnants, of prior human occupation. Although the recovery of submerged, intact cultural artifacts is rare, researchers have found that microdebitage—microscopic stone fragments (< 1 mm) generated during tool production—can be easily extracted and identified in sediment cores taken near tool-making sites. For example, researchers employed microdebitage analysis to identify a Late Paleoindian–Early Archaic-age tool-manufacturing site in the eastern Great Lakes region of North America (Sonnenburg, Boyce, and Reinhardt 2011). This method has strong potential to identify submerged historical sites, which is difficult because of their scarce nature and the rapid burial they experience in lacustrine environments.

In the absence of physical remains of archaeological artifacts, the unequivocal evidence of anthropogenic activity can still be detected using distinct biogeochemical compounds archived in lake sediments. Fossil biomarkers preserved in sediment cores continue to be developed to provide information on past human activities, including cultivation and pastoral activities and subsequent environmental effects such as biomass burning, vegetation shifts, and soil erosion (see ENVIRONMENTAL MANAGEMENT WITH FIRE; EROSION; and PALYNOLOGY).

One of the more promising indicators is fecal biomarkers, which can detect the presence of prior human and other animal activity. Feces from different species of vertebrates have variations in their contents of specific steroids due to differences in diet, ability to generate endogenous steroids, and the presence/absence of different anaerobic gut bacteria (Prost et al. 2017). Human feces, for example, have high concentrations of coprostanol, whereas herbivores have higher amounts of 5 β -stigmastanol relative to coprostanol contents. Researchers used fecal sterols from lake sediments in northern Norway to document the first occupation of humans and their livestock over 2,000 years ago (D'Anjou et al. 2012). The human activity could be subsequently

linked to an increase in landscape fires and a decline in woodland, which helped disentangle the effects of anthropogenic versus natural factors on the environment. Similarly, in the Canadian High Arctic, epicoprostanol (which has a distinctive presence in human sewage and in animal waste not endemic to the Arctic such as pigs, poultry, and magpies) has been used as a sediment biomarker to detect ancient human activity (Cheng et al. 2016).

Environmental reconstructions

Climate, the environment, and human culture are inextricably linked. Paleolimnological records can complement archaeological studies to provide a holistic picture of environmental and climatic conditions under which past societies burgeoned and collapsed. Nowhere, perhaps, is this better exemplified than on the Yucatan Peninsula where scientists have used sediment records to explore climate–environment interactions and ancient Maya society since the late 1950s.

Pollen records from sediment cores in the Maya Lowlands indicate the disappearance of a tropical forest occurring more than 3,000 ^{14}C years BP, which generally coincided with the expansion of Early and Middle Preclassic Maya populations. Traditionally, it was viewed that human activities were largely responsible for the forest decline and any climatic influence was negligible, but later research showed that climatic drying may have also played a role (Brenner et al. 2002). Likewise, researchers have shown a link between drought conditions and sociopolitical evolution in the southern Maya Lowlands. Using hydrogen and carbon isotopes of plant wax lipids preserved in lake sediment cores, Douglas et al. (2015) showed that relatively wet and stable conditions during 700 BCE to 200 CE were marked by continuous growth and increasing sociopolitical complexity, including the rise of large population centers, writing, and public monuments. Dry conditions, beginning ca. 800 CE, coincided with a decline in political complexity, including the end of monument building and written inscriptions and the cessation of centralized kingship (the main political entity of the Southern Lowlands for the first millennium CE). This political decline was not followed by any new, resilient political

centers, which led the researchers to conclude that the lack of any recovery in the Southern Lowlands was due to sustained drought conditions.

In summary, paleolimnologists have a long record of successfully reconstructing past environmental conditions that may be especially relevant to archaeologists (e.g., temperature fluctuations, drought cycles). Equally, they have a long record of reconstructing the effects of past human activities on ecosystems, which may provide important data and insights to archaeological studies. Paleolimnological data still represent a largely unused resource for archaeologists, but many new collaborative efforts are now being initiated.

SEE ALSO: Paleoenvironmental Reconstruction; Soil Chemistry in Archaeology; Varve Chronology

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Land and Freshwater Molluscs

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Two classes of animals in the phylum Mollusca can be found in freshwater: bivalves and gastropods; gastropods may also be found on land (Figure 1). Bivalves have shells of two roughly equal-sized valves, hinged together. Many gastropods (“snails”) have external shells (often spiral) into which they can withdraw when inactive; some of these have a corneous or calcareous operculum attached to the foot which can seal the aperture of the shell for added protection against moisture loss. Other gastropods (“slugs”) lack a prominent outer shell, but some have a small internal shell (“slug-plate”).

The hard shells of molluscs consist of a number of layers. The outer layer, or periostracum, is composed of a protein called conchiolin. This often degrades quickly after burial (and in some cases may be abraded during life). The inner layers are made of calcium carbonate in complex arrangements of either of its crystalline forms, aragonite or calcite; sometimes both forms are present in the same shell. Because they are calcareous, shells preserve well where pH is high. This makes them complementary to pollen, which tends to preserve well where pH is low. Mollusc shells occupy a wide size range, from the large tropical Achatinidae, which can reach 30 cm in height, to *Angustopila dominikae* from China, around 0.86 mm in height. Most species are a few millimeters in their largest dimension, and so recovery during archaeological fieldwork requires sediment sampling (see SAMPLING IN ENVIRONMENTAL STUDIES), rarely supplemented by hand collection of shells.

Molluscs as proxies for past environments

Shells were noted in archaeological deposits in the nineteenth century, and in the first half of the twentieth century, and lists of the species represented at different sites began to be compiled. Knowledge of the preferred habitats of different species of land and freshwater molluscs in modern times began to be systematized in the middle of the twentieth century (for most of the world, this work is ongoing), which allowed researchers like Michael Kerney and Brian Sparks working in the United Kingdom to explore how changes in the species composition of shell assemblages through time reflected environmental change (Davies 2008, 1). The archaeological study of snails came of age with the publication in 1972 of the first book on the subject, *Land Snails in Archaeology* by John G. Evans. Subsequently, studies have been carried out globally, extrapolating from, and developing, the methods framed by Evans.

From the middle of the twentieth century, molluscan zonation schemes were created in southern Britain and some areas of continental Europe by Michael Kerney and others, the “zones” being stratigraphic associations of taxa which change in response to climatic variation. Another methodology for climatic reconstruction was developed in the late 1980s using Coleoptera, which has subsequently been applied to other biological groups including Mollusca (Moine et al. 2002). Known as the “Mutual Climatic Range” method, it relies on the climatic tolerances of particular species in the present day. The past climate of a location can be defined by the overlapping range of climatic conditions which would permit the taxa present to coexist, and is expressed in terms of the mean temperature of the warmest and coldest months (TMAX and TMIN).

Unlike some other invertebrates, in particular insects (see ARCHAEOENTOMOLOGY), molluscs tend not to be restricted to consuming a single

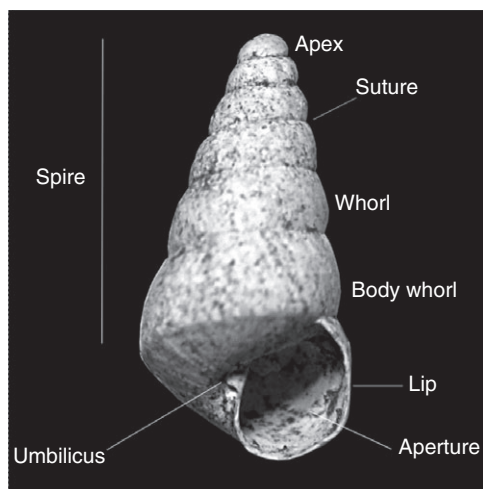


Figure 1 Anatomical terms for gastropod shells.

plant species, so they do not make good proxies for the presence of individual plant species. Some snail species, known as stenotopic species, have very narrow ecological tolerances across their whole range, however, in particular in environments that are subject to extremes (such as wet ground that dries out seasonally). These may be used as indicator species in paleoecology, although many stenotopic species are also very rare and so have limited utility. In general, however, the ecology of individual species depends on an often complex mix of variables, which each may vary in relative importance at different times or in different localities.

This problem has been overcome in paleoecology by the observation that modern, living snails occur in associations with particular relative abundances and that distinctive assemblages of snail recur in some paleoecological contexts. As these tend to be limited to a single taxonomic group in paleoecology, the term taxocene is used to describe these associations. Taxocenes are taxonomic segments of communities, and the members of a taxocene are likely to be closely analogous, having a similar size and similar life histories, and competing over both evolutionary and ecological time.

In the British Isles, molluscan studies have been especially productive where numerous sites of similar date have been explored within a region, for example the Wiltshire chalk or coastal machair of the Western Isles of Scotland. This has

allowed contrasting ecologies at a local scale to be detected and a detailed picture of human impacts on the environment to emerge (see Davies 2008 for a review).

A number of cautionary notes should be sounded when looking at molluscan assemblages, however. In many scenarios, rates of sedimentation are slow, meaning that shells found within the same depth range were not necessarily alive at the same time. At the very best, the shells recovered from a sample represent shells that became subfossils over the entire time it took the part of the deposit sampled to accumulate, and so are likely to represent a mix of the communities that existed during the period the deposit was laid down, rather than any particular community. Also, molluscan communities, although sensitive to change at a very local level, may respond to environmental change on a scale of decades rather than months or years, with the result that there is a theoretical lag in the site biostratigraphy between an environmental change taking place and it being detectable in the molluscan assemblage. In practice, slow rates of sedimentation may mask this lag. As Thomas (1985) has noted, despite theoretical problems, land snail analysis in archaeology has “worked” because the data make ecological sense.

Where variation in shell form exists within a single species, it can be quite revealing. For example, the European land snail *Discus rotundatus* has been shown to grow “taller” (that is, with a larger spire) in wetter conditions, and the coloring of the periostracum in some species can reflect the degree of vegetation cover, as these larger snail species may be subject to predation by birds. Goodfriend (1986) reviews a number of species worldwide that show such phenotypic plasticity which may have archaeological relevance—commonly, shells of many species (generally larger species, in particular Helicidae) may be larger with higher rainfall, larger on high-calcium soils, and smaller with higher population density.

Mollusc shells are also suitable for isotopic analyses. Oxygen isotope ratios may be used to reconstruct past temperatures, the $\delta^{18}\text{O}$ in the shells being primarily controlled by water ingested by the mollusc. However, in both terrestrial and especially freshwater shells a number of environmental variables may influence the

$\delta^{18}\text{O}$ of shell carbonate. In the case of molluscs collected for food, oxygen isotope analysis of the final growth increment (in gastropods, the edge of the shell lip; in bivalves, the outermost edge of the shell) may reveal the season of harvesting. $\delta^{13}\text{C}$ values in shells may be indicative of plant water relations in areas where C_3 plants dominate (Yanes et al. 2013).

Molluscs as food and medicine

Various larger species of land and freshwater mollusc are edible. These include larger Helicids such as *Helix pomatia*, *Helix lucorum*, *Cornu aspersum*, and *Theba pisana* in Europe, western Asia, and North Africa, and the giant land snails such as *Achatina achatina* and *Archachatina marginata* in Africa. Human terrestrial malacophagy has a long history: concentrations of cooked shells of *Iberus alonensis*, associated with structures thought to have been used for cooking, have been found at the Upper Paleolithic site of Cova de la Barriada, Spain (Fernández-López de Pablo et al. 2014). Various freshwater bivalves are also edible.

Some molluscs are vectors for endoparasites affecting humans; for example, the nematode *Angiostrongylus*, which can live within humans as an incidental host and cause meningitis, uses various edible molluscs as an intermediate host. A number of nonmarine mollusc species are used in traditional medicine; for example, the freshwater apple snail *Lanistes lybicus* is used in the treatment of conditions such as measles, ear complaints, and eye problems in Nigeria.

The dispersal of molluscs

Nonmarine molluscs may be dispersed through a number of means, including rafting across water on vegetation and being carried on the plumage of birds (or even internally, in some cases to emerge alive from the other end). The movement of people and goods is often implicated, however. Edible species may be deliberately transported live, as is probably the case with the arrival of *Helix pomatia* in Britain. Other species may be accidentally transported in cargo, for example the shells found within amphoras of terebinth resin on board the Bronze Age Uluburun shipwreck near

Turkey (Welter-Schultes 2008). Genetic analyses of living populations can be used to establish linkages between distant populations and, by proxy, identify routes of past human movement.

Molluscs and scientific dating

Mollusc shells are suitable for a number of isotopic dating techniques, including radiocarbon dating, especially when accelerator mass spectrometry (AMS) is applied, and particularly species with small shells. To be suitable for radiocarbon dating, the ^{14}C activity of mollusc shells must be in equilibrium with that of the atmosphere while the animal is alive, and the shell must be a closed system with respect to carbon after death. Pigati, Rech, and Nekola (2010) found that ca. 78 percent of shell aliquots from the smaller species of gastropod they studied living on carbonate terrain contained no old carbon, in contrast to reports of 20–30 percent dead carbon in some larger taxa, suggesting that larger taxa may yield unreliable dates. Other radiometric techniques applicable include uranium series dating (see URANIUM-SERIES). It can be applied beyond the range of radiocarbon dates, to materials from dates as old as 500 kya.

Some snail shells have proven to be particularly suitable for amino acid dating. Due to temperature-dependent variability in amino acid racemization, it can be hard to assign a definitive age to samples unless there is independent calibration available; however, the method can also be applied to establishing relative chronologies, a technique known as aminostratigraphy. It is best to use multiple samples, and to ensure that peptide-bound amino acids are also analyzed, in order to overcome problems of shells being chemically compromised (Penkman et al. 2007). The calcitic opercula of the freshwater gastropod *Bithynia* have been found to be especially suitable for amino acid dating as they have greater chemical stability than shell (Penkman et al. 2011).

SEE ALSO: Isotopes; Marine Molluscs

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Llamas and Alpacas

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Introduction

South American camelids are artiodactyla mammals mainly distributed in the Andean area. The taxonomic classification of these animals places them in the Camelidae family, with two genera, *Lama* and *Vicugna*. Furthermore, four species are distinguished: Two are wild and the other two domesticated. The former comprise the vicuña (*Vicugna vicugna*) and the guanaco (*Lama guanicoe*), the latter the alpaca (*Vicugna pacos*) and the llama (*Lama glama*).

Modern vicuñas live in areas higher than 3,000 m asl in the Andes mountain range. The high plains in the Andes are known as *Puna* and constitute environments with different determinants for adaptation, such as hypoxia. These wild camelids feed on grasses spread in patches throughout the Puna and their social organization is based on territorial family groups and single groups. Vicuñas are the smallest animals in the Camelidae family, with an average weight of 45 kg.

Guanacos have a wide latitudinal and altitudinal distribution, from sea level (e.g., in Patagonia) to more than 4,000 m asl (on the Puna). They are herbivores, like the rest of camelids, and they also live in family and single groups. They are larger in size than vicuñas, with an average weight of 100 kg. However, their size varies depending on the latitude; for instance, larger animals are found in Patagonia than in northern Argentina and the Chilean Andes (Mengoni Goñalons and Yacobaccio 2006).

Llamas and alpacas are domesticated animals distributed throughout the Andean area. Alpacas prefer more humid environments, avoiding the arid Puna of the Central-South Andes (e.g., Argentinean Puna) and mainly inhabiting the more humid Puna in Peru and Bolivia. They weigh around 50/60 kg. Llamas, on the other

hand, are larger, weighing between 80 and 150 kg. They occupy different sectors of the Andean highlands and are adapted to the arid environment of the Puna, and are thus more widely distributed.

South American camelids were protagonists of a coevolutionary relationship with humans. Changes during the Holocene included intensification and domestication; this entry aims to analyze and briefly discuss these changes from an archaeological perspective.

Change processes and archaeological evidence

Human consumption of camelids has been recorded since around 11,000 years BP even in contexts where Pleistocene megafauna were present, such as the Pampa plains and Patagonia (e.g., Martin et al. 2015). Thus, camelids have been the most important protein source for human populations of different South American regions for more than 10,000 years.

Nevertheless, only in certain sectors of the Andean area did the coevolutionary process result in camelid domestication. Yacobaccio and Vilá (2013) present a model which involved different mechanisms of natural and artificial selection operating in this process. In a first phase—broadly the Early Holocene (ca. 11,000–8000 BP)—a generalized hunting would have developed. By the Middle Holocene (ca. 8000–3500 BP), increasing regional aridity had produced a greater segmentation of the landscape, creating patches of resources with subsequent concentration of humans and camelids in certain spaces. The reduction in mobility, increase in human group size, and growing demand for food would have promoted a process of intensification in camelid use. Similar processes of intensification are seen with other animals and plants in different parts of the world, linked to higher social complexity in human groups (see DOMESTICATION). Diverse indicators, fundamentally the increasing archaeological evidence coupled with radiocarbon

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dates, would indicate population growth towards the end of the Middle Holocene in the Puna (ca. 5000 BP) (Muscio and López 2016). This chronology coincides with evidence of camelid domestication at a macroregional scale. Following Jacobaccio and Vilá's model (2013), the stage previous to domestication, namely the development of protective herding mechanisms, is indicated by human groups facilitating access to grasses for camelids and providing them with protection against predators. Finally, the animals were separated and held in captivity, leading to domestication.

Broadly speaking, intensification may be defined as the search for a higher productivity per space unit or resource. Domestication implies a process where animal and/or plant populations adapt to humans and the environment through genetic change over many generations along with developmental events which are environmentally induced (Jacobaccio and Vilá 2013). Research carried out in the last few decades has been able to establish the ancestors of domesticated species. In the case of alpacas, the current view considers the vicuña as their wild ancestor (Kadwell et al. 2001). Domestication of alpacas from vicuñas would have developed in the Central Andes between 7000 and 6000 BP (Wheeler 1999), although some authors propose later dates (5000–4000 BP) (Marshall et al. 2014). On the other hand, llamas derive from the domestication of guanacos. Archaeological evidence of this process suggests that this occurred between ca. 5000 and 3500 BP, though earlier records are also known (Mengoni Goñalons and Jacobaccio 2006). DNA studies were fundamental to defining the origin of domesticated camelids (see ZOOARCHAEOLOGY AND ANCIENT DNA). However, recent studies show that interbreeding occurred and that this process was more complex (Marshall et al. 2014).

Figure 1 presents the location of some of the sites with evidence of changes related to camelid domestication. In the Central Andes, specifically in the Puna de Junín, Peru, the Telarmachay site recorded changes leading to the domestication of alpacas in ca. 6000 BP (Wheeler 1999). Other sites in the Puna de Junín such as Pachamachay and Panaulauca yielded evidence of domesticated camelids ca. 4000 BP. To the south of Peru, the Asana site also indicated changes toward camelid domestication in ca. 3600 BP (Aldenderfer

1998). Furthermore, in northern Chile and the Argentinean Puna, several sites reported evidence of domestication and/or presence of domesticated camelids by ca. 5000 BP. In the Atacama Puna, Chile, such changes were detected in the archaeofaunal record at Tulán 52 and Puripica 1 (Cartajena 2013). Additionally, in the highlands north of Argentina, sites such as Inca Cueva 7 (ICc7), Alero Unquillar, Huachichocana III (Ch III), Abrigo Pozo Cavado (APC), Alero Cuevas, Quebrada Seca 3, and Peñas Chicas 1.5 also produced evidence of changes leading to camelid domestication, particularly in llamas (López and Restifo 2012; Jacobaccio and Vilá 2013).

Several analyses were used to study these processes, such as dentition, osteometry, age at death profiles, characterization of fibers, and contextual analysis. As aforementioned, DNA analysis was fundamental to the progress of these studies.

Regarding dentition, variability in incisors was used to define the presence of alpacas in early contexts in the Central Andes (Wheeler 1999). Furthermore, osteometry was applied in the Andean area to distinguish the different species of camelids by measuring bone size. These analyses were crucial to differentiate domesticated from wild camelids. Additionally, age profiles were similarly considered as evidence for domestication (Wheeler 1999). An increase in subadult camelids, particularly newborns, is seen at several sites in the Central Andes, particularly Telarmachay (Wheeler 1999). These changes are interpreted as the result of diseases caused by the animals being kept in confined conditions during the process of domestication. In other contexts of the Central-South Andes, the high representation of subadults could be related to a process of intensification of hunting to satisfy the higher demand for food (López and Restifo 2012), although it is possible that both processes (intensification and domestication) happened in conjunction (López and Restifo 2012). Other evidence for distinguishing among camelid species is the variability in their fiber (see FIBERS). The record at Quebrada Seca 3, in the Argentinian Puna, indicates the presence of camelid fiber similar to llama's at early times (ca. 9000 BP) (Reigadas 2008). Lastly, contextual indications such as the presence of dung layers or corrals are relevant for the study of domestication. At Inca Cueva 7 (ca. 4000 BP) and Asana (ca. 3600

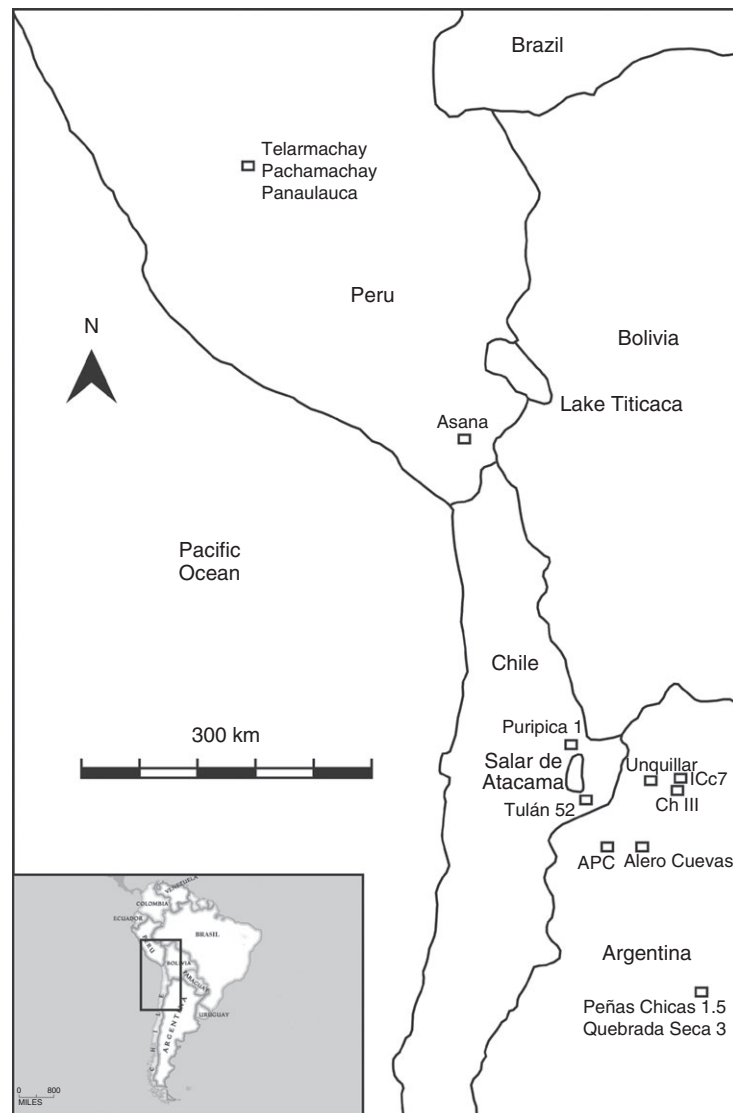


Figure 1 Archaeological sites with evidence of changes toward camelid domestication in the Andes.

BP) there is evidence of camelids in captivity (Aldenderfer 1998; Yacobaccio and Vilá 2013).

In recent decades, research on camelids has diversified. Techniques and approaches include taphonomic analysis (see TAPHONOMY), consideration of the age and sex structure of camelids, and research on stable isotopes (see ZOOARCHAEOLOGY AND STABLE ISOTOPES). The many lines of evidence can be used to explore changes in human society. This entry has focused on the processes of camelid intensification and domestication in the Andean area, but other questions can be explored.

Camelids have provided the main animal food resource for the different populations in South America for 10,000 years. Hence, research on the relationship between camelids and humans will certainly open new areas of enquiry in the future.

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Maize

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As early as 1945, Isabel Kelly's excavations along the Tuxcacuesco reach of the Rio Armeria in southwestern Jalisco, Mexico produced significant evidence of agricultural dependence on maize, agave, and other forest products. Edgar Anderson (in Kelly 1949) described the first archaeological evidence—a carbonized cob—as a narrow rachis with ten rows of grain. The suggested date, by ceramic association, was Pre-Classic West Mexico (ca. 350 BCE to 300 CE). In the 70 years since Kelly's findings when morphological description of macroscopic remains from relatively dated contexts was possible, we now routinely date macrobotanical evidence directly. Indirect dating of microscopic phytoliths from stratigraphic profiles or from grinding stones is still the norm. Significant improvements now permit modeling the rates of genetic change in maize since teosinte's domestication and the impact of climate change on Mexican annual teosintes and land races (Hufford et al. 2012a; 2012b; Swarts et al. 2017).

Archaeological evidence of maize agriculture includes: pollen, phytoliths, starch grains, corn cobs, and macroscopic remains of maize and its wild relative teosinte; isotopic signatures in the animals that consume maize, including humans; ancient DNA; ceramic representations; corn preparation tools and residues they adhere to; and linguistic and pictorial representations on many graphic media (Staller, Tykot, and Benz 2006). All these materials add to our knowledge of how and when maize was utilized and the role it has played in ancient societies. All materials come with certain caveats and all have their proponents and critics. This entry briefly describes the archaeological evidence for the early use and domestication of maize, with particular reference to recent research. It focuses on dating evidence, macrobotanical material, pollen, phytoliths, and starch grains (Figure 1).

Types of archaeological material

The types of evidence used by archaeologists to make inferences about the origin and evolution of maize have, until recently, been limited to macrobotanical material (see PALEOETHNOBOTANY), pollen (see PALYNOLOGY), phytoliths (see PHYTOLITH ANALYSIS), and starch grains (see STARCH GRANULE ANALYSIS). However, ancient DNA analysis (see PALEOETHNOBOTANY AND ANCIENT DNA ANALYSIS) is now becoming common in the archaeological literature (Swarts et al. 2017).

Pollen grains have been long associated with maize research. Since the discovery of pollen grains at Guila Naquitz, Oaxaca, Mexico by Schoenwetter (1974), numerous studies on sediment cores from archaeological contexts, estuaries, lakes, and coastal swamps have found evidence for maize and teosinte (Blake 2015; Blake et al. 2017; Staller et al. 2006). However, because maize has pollen grains that cannot be reliably distinguished from teosinte or *Trip-sacum*, care should be taken when interpreting the evidence (Holst, Moreno, and Piperno 2007).

In the Gulf of Mexico, the San Andres locality in Tabasco yielded a long sequence—7100–2486 cal. BP (median years calibrated radiocarbon date before present; all subsequent reports follow this format)—containing *Zea* pollen, showing an increase in size up through the sequence which was interpreted as reflecting the evolutionary sequence from teosinte to maize. Pollen from Zohapilco, near Chalco, Mexico occurred at 4795 cal. BP and was dated by association with two teosinte fruit cases. In Belize, the site of Cob Swamp in Corozol likewise produced indirect dates (stratigraphically associated) dating from 5341 to 2876 cal. BP. In Guatemala, the Sipacate site in Escuintla produced *Zea* pollen from 5489 to 3090 cal. BP. *Zea* pollen occurred twice at Lago Puerto Arturo, Peten, Guatemala, at 5172 and 3224 cal. BP, while at Rio Naranjo, San Marcos, Guatemala, *Zea* pollen was found at depths dated 4611 and 3825 cal. BP. In Central America, *Zea* pollen was recorded at around 5512–4988

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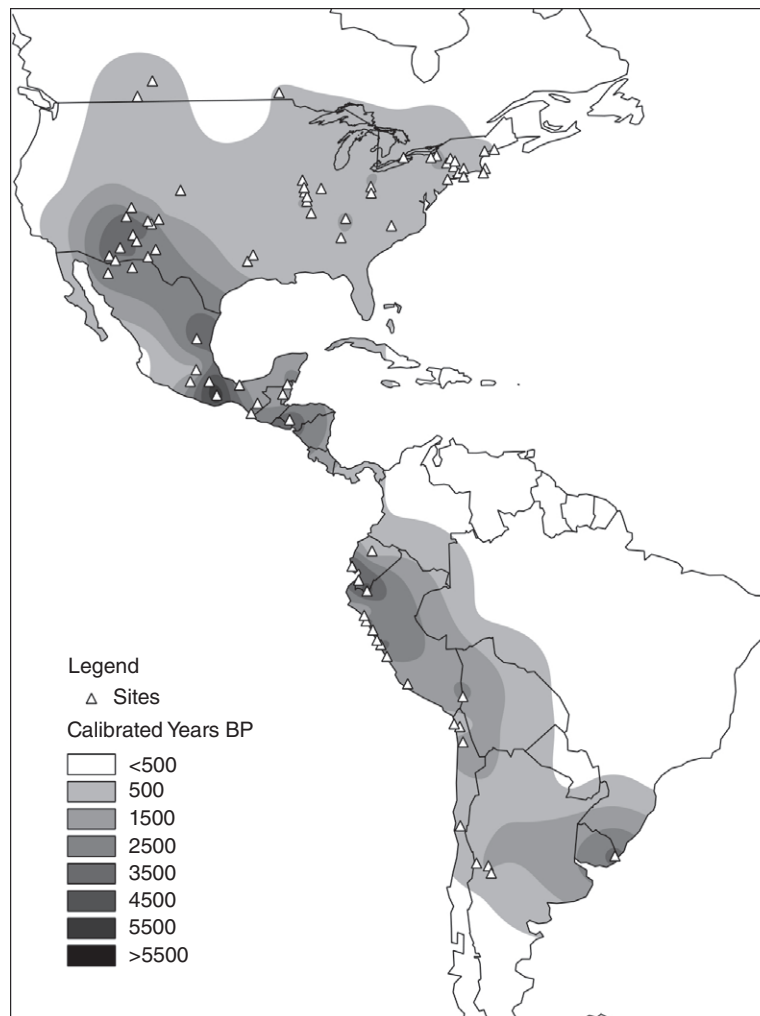


Figure 1 Distribution of maize antiquity based on pollen, phytoliths, starch grains, and macrobotanical material dated directly.

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cal. BP at Laguna Martinez, Guanacaste, Costa Rica. A very similar age date (5464 cal. BP) on associated pollen came from Lake Yojoa, near Cortes, Honduras. In Colombia, the date 5357 cal. BP associated with *Zea* pollen came from El Dorado, Yotoco, Valle del Cauca. Pollen of *Zea* was also encountered in Araracuara, Solano, Caqueta, Colombia (5302 cal. BP), and much later at Araracuara 3 (around 1017 cal. BP). Pollen grains identified as *Zea* occurred at three separate depths of 5156, 3488, and 2460 cal. BP

in Lake Ayauchi, Morona Santiago, and Ecuador, respectively. *Zea* pollen was found in the cultural deposits of Los Gavilanes, Huarmey, Ancash, Peru dated to around 4591 and 4044 cal. BP, and at Caballete, north of Lima, Peru at 4449–3982 cal. BP and nearby Porvenir around 4732 cal. BP. To the north, pollen occurred in lake sediments only 663 and 667 cal. BP years ago in Laguna Castilla, Azua, Dominican Republic. In New Mexico, *Zea* pollen was recorded in a pack rat midden (CC3) in San Juan, and in New Mexico twice, at 4383

and 2767 cal. BP. It was also found as far north as the Crawford Lake site, Campbellville, Ontario at around 672 and 663 cal. BP (Blake et al. 2017).

Early occurrences of maize phytoliths were documented in Monte Oscuro, Panama, dating from 8311 and 6749 cal. BP. The Aguadulce rock shelter in Cocle, Panama produced phytoliths dating from 7746 to 7102 cal. BP. Chirique, Panama produced phytoliths at 7141 cal. BP and again at 6732 cal. BP. Cueva de Los Ladrones and Aguadulce yielded phytoliths on tools and in midden samples at around 7701 and 7101 cal. BP, respectively. To the north and west, coastal swamp sediments from SOC 05-2, Pijijiapan, Chiapas, Mexico were dated to around 6589 cal. BP. San Andres, Tabasco, Mexico also produced a few phytoliths, these occurring in association with the earliest pollen at 7101 cal. BP. Samples from the Las Vegas site, Santa Elena, Ecuador produced phytoliths indirectly dated at 7915 cal. BP. Phytoliths appear at Huaricanga and Porvenir north of Lima at 4873 and 4732 cal. BP, and in Waynuna, Condesuyas, Arequipa, Peru from 4029 until 3721 cal. BP. Phytoliths are recorded much later in New York: at Fortin, South Kortright dating to 1945 cal. BP; and then 1409 cal. BP and 1941; at Vinette, Oswego dating to 1890 cal. BP; and from 1358 to 1330 cal. BP at the Kip Island site, Cayagu. Phytoliths also occur slightly later—1163 and 1138 cal. BP at the Hunter's Home Site, Savannah, New York (Blake et al. 2017).

Starch grains of maize have been recovered on tools and ceramic vessels. These grains have been identified from numerous sites throughout the Americas (Blake 2015; Blake et al. 2017; Staller et al. 2006). Most are dated indirectly. The earliest come from tools in contexts dated 8750 cal. BP at Xihuatoxtla, Huizuc de los Figueroa, Guerrero, Mexico. Starch grains reoccur at Xihuatoxtla in association with dates of 5475, 2891, and 1126 cal. BP. Panamanian research produced starch grains in association with tools at Cueva de los Ladrones and Aguadulce at around 7707 and 7702 cal. BP, respectively. Starch grains were found on a single Archaic (6655 cal. BC) stone tool at Caye Coco, Corozal, Belize. The Valdivia culture site of Loma Alta, Guyas, Ecuador produced numerous occurrences of starch grains dating from 5647 to 4982 cal. BP, though maize macroremains do not appear until 2,500 years later. Santa Ana-La Florida in the Ecuadorian highlands yielded

dated samples and associated starch grains at 4979 cal. BP. Sites on the Peruvian coast have produced artifacts with starch grains that are slightly later in date to the Ecuadorian coastal sites; Huaricanga near Lima, Peru produced dated contexts with starch grain-laden tools at 5159 and 4873 cal. BP (Blake et al. 2017).

Maize cob fragments, cupules, and kernels are much more numerous in the archaeological record than any other types of evidence for this species; most occur in Mexico. The earliest macroscopic corn cobs appear at 6229–6222 cal. BP at Guila Naquitz, on the northern margin of the Central Valley of Oaxaca, Mexico. Their morphological characteristics indicate domestication (Benz 2001), though they are not typical of the cobs found today. Around 800 years later, numerous cobs occur within rock shelters in the Tehaucan Valley, Puebla, beginning at San Marcos (5434–4689 cal. BP), Coxcatlan (4545–4098 cal. BP), and El Riego (4272 cal. BP). Maize persists at these localities until the time of Spanish contact. Maize cobs and teosinte occur coincidentally in the strata of El Romero's cave in southern Tamaulipas, Mexico, at around 4630–4380 cal. BP. Not long after, maize appears in New Mexico at the appropriately named Old Corn site, with cobs, cob fragments, and kernels dating between 4207 and 3932 cal. BP. Maize from McEuen Cave overlooking the Gila River in eastern Arizona (4030 cal. BP) and from Three Fir shelter in Navaho, Arizona (3940 cal. BP) in northeast Arizona is of slightly more recent origin, as are numerous maize kernels at sites in the Santa Cruz river basin northwest of Tucson, Arizona at Clear Water (4061–4030 cal. BP) and Las Capas (4003 cal. BP). Other sites in the Tucson Basin represent a persistence of maize agriculture that begins at Los Pozos at around 3720–3246 cal. BP and reappears from 2345 until 2141 cal. BP. The Los Pozos hiatus is bridged at El Milagro (3090–2878 cal. BP), Costello-King (2884–2746 cal. BP), Solar Well (2965–2235 cal. BP), and Cortaro Fan (2897–2858 cal. BP) (Blake et al. 2017).

Meanwhile, far to the south and east of Guila Naquitz, the site yielding the most ancient maize to date, the rock shelter known as El Gigante in La Paz, Honduras, yielded cobs as old as those from the Old Corn site in New Mexico (4373–3997 cal.

BP). Maize persists through the cultural strata at El Gigante up to the time of Spanish contact.

Even farther south, the site of Paredones, Ascope, La Libertad, Peru produced a wealth of maize, some of it securely dated at around 4861 cal. BP. Other specimens have aberrant C^{13} values, suggesting contamination. The nearby site of Huaca Prieta also contained maize cobs that dated to 4074 cal. BP. Maize is common in sites along the Pacific coast of Peru and Chile, most of which are more recent than the cobs from the Ramaditas site in Provincia Iquique, Primera Región de Tarapacá, Chile (2154 cal. BC) (Blake et al. 2017).

Grains and cob fragments dated to the second millennium BCE (2000 cal. BP) occur in the United States: including Georgia, at the Rush site, near Floyd (1444 cal. BCE); Tennessee, at the Ice House Bottom site near Jamestown (1698 cal. BCE); Ohio, the Edwin Harness Site, near Groveport (1647–1637 cal. BCE); and Illinois, the Crane site near Greene (1402 cal. BCE). Two dates on maize cupules from the Grand Banks site near Cayuga, Ontario are of similar antiquity (1468–1421 cal. BCE).

When was maize domesticated?

According to recent genetic research, maize evolved from its ancestor teosinte (*Zea mays* ssp. *parviglumis*), and experienced some introgression from highland teosinte (*Zea mays* ssp. *mexicana*) (Hufford et al. 2012a; van Heerwaarden et al. 2011) prior to dispersal in its current form. The antiquity of this process is hypothesized by some to have occurred slightly less than 9,000 years ago, and by others at around 6,300 years ago. The tropical lowlands of West Mexico appear to have been the locus of early maize evolution. The timing of the domestication process is clouded by a plethora of pollen, phytolith, and starch grain finds, most of which are indirectly dated and uncorroborated by associated macrobotanical evidence—with macrobotanical evidence only occurring 2,500 years later. On the other hand, the macrobotanical evidence clearly documents the domestication syndrome of crop plants' phenotypic evolution, followed by gradual evolutionary increase in grain number and size. This evolutionary process has not been documented

in the tropical lowlands of western Mexico, where genetic evidence suggests it should occur, but at mid-elevation localities—Guila Naquitz, Tehuacan—distant from the site of presumed domestication. The domestication of maize is well documented from a genetic point of view, but less well archaeologically. The confluence of these two areas of study is providing new insights (Swarts et al. 2017). Stay tuned.

SEE ALSO: Domestication

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Marine Molluscs

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Shells of marine molluscs from archaeological contexts can inform about the environmental, chronological, subsistence, behavioral, and social contexts of people in the past. Studies of marine molluscs in archaeology have a long history, but in recent years these have proliferated greatly, alongside increasingly diverse analytical methods and research applications.

Molluscs occur in most environments occupied or exploited by humans. Although particularly diverse in marine environments, they have adapted to nonmarine habitats (see LAND AND FRESHWATER MOLLUSCS). Bivalves (clams) and gastropods (sea snails) are the groups most frequently found in archaeological deposits; other marine groups (chitons, scaphopods, and cephalopods) occur less frequently. The ecology of species is also highly variable, making them good indicators of past environments.

In many coastal regions of the world, huge numbers of shells, principally species with high food value, form the main component of shell middens, some occurring as large topographical features. Most of the marine molluscs found in archaeological deposits inhabited the inter-tidal zone of shores where they could be collected at low tides, although shallow-water subtidal species can be obtained by diving. The empty shells of deeper-water species can be cast up onto shores by storms or strong wave action and be collected by people. Marine shells also occur at inland archaeological sites, such as within inhumations, with small perforated shells of ornamental or symbolic significance.

The recovery, identification, and quantification of assemblages of marine shells from archaeological sites is covered by Claassen (1998) and Harris, Weisler, and Faulkner (2015). Once the species and their numerical abundance are established, interpretations can be made of past

human choices of the species gathered and the types of shores exploited. A preponderance of large edible species suggests collection for consumption, while smaller shells might have been collected as ornaments. While useful information can be gained from the composition of the assemblage, various analytical procedures can reveal much more.

Most marine molluscs grow their calcareous shells throughout life, growth being added incrementally at the shell edge in bivalves or the aperture in gastropods. These growth increments constitute a time-series, or sclerochronology (Greek: *scleros*, hard; *chronos*, time) which records environmental conditions experienced by the animal over its life; for more about sclerochronology see Andrus (2011). Bivalves have provided the highest levels of resolution of shell growth intervals and been most studied, although gastropods are increasingly being investigated. The integration of sclerochronology with analyses of stable isotopes of oxygen ($\delta^{18}\text{O}$) and carbon ($\delta^{13}\text{C}$) in shell carbonates (see Leng and Lewis 2016) is a powerful tool for investigating past climate, environmental change, and past human behavior.

Marine shells are suitable for radiocarbon dating by accelerator mass spectrometry, provided caution is exercised in the selection of shells, and in calibrating and interpreting the dates. Shells selected for dating should represent human activity close to the time of the death of the mollusc, such as food discard. Dates are generated from the calcium carbonate in shells and mineral diagenesis can lead to either older or younger carbon being incorporated into the shell crystals, distorting the resulting date. Macroscopic and microscopic indicators can help identify recrystallized marine shells. The marine reservoir effect, where old carbon becomes incorporated into the growing shell, can produce dates that are too old. Reservoir age variations (ΔR), calculated from radiocarbon determinations on marine animals (often mollusc shells) of known chronological age, are widely available for local corrections and calibrations. Knowing ΔR for a coastal region or locality is essential for the calibration of radiocarbon determinations using a marine calibration

curve. Filter-feeding (predominantly bivalve) molluscs have been preferred for dating purposes because their principal carbon sources are phytoplankton and dissolved inorganic carbon in the seawater. Gastropod shells have been less favored because they can ingest deposits with either enriched or depleted radiocarbon as they graze, although perfectly acceptable radiocarbon dates have been obtained from selected gastropod species. Recent improvements in laboratory techniques, such as the recovery of intracrystalline amino acids, offer hope for reliable amino acid racemization dating of marine shells. For further discussion of dating of mollusc shells and references to key literature, see Thomas (2015a).

Large accumulations of shells of edible molluscs could indicate they were a significant human food resource in the past, although this significance is reduced if caloric contribution is taken into account. There are, however, more facets to diet than calories alone and marine molluscs provide important nutrients such as proteins and trace elements. They are available and easily procured at all times of year, including times when alternative food sources might be scarce. The relative importance of marine molluscs and other marine food in past human diets is increasingly being investigated through the stable isotopes of carbon, $\delta^{13}\text{C}$, and nitrogen, $\delta^{15}\text{N}$ (see DIET AND CARBON ISOTOPES and DIET AND NITROGEN ISOTOPES) in collagen extracted from human bones. Such studies have shown, for example, that while marine foods were significant in Late Mesolithic (6th millennium BCE) hunter-gatherer diets along the Atlantic coast of Europe, in the Mediterranean they played a minor role in hunter-gatherer diets. Most marine molluscs are either primary consumers or detritivores and have $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ values close to those of marine algae; therefore their consumption by humans would give only a weak “marine food” isotope signal compared with higher-trophic-level marine animals, such as fish (see FISH).

Oxygen isotope data ($\delta^{18}\text{O}$) on season of harvest of marine molluscs can be useful for studies of past human subsistence. A mollusc dies when harvested by a forager, and the temperature-related $\delta^{18}\text{O}$ signature in the final growth increments of its shell indicates when in the year this happened. To determine seasonality of collection, the $\delta^{18}\text{O}$ values in shells must

record full annual temperatures; that is, shells must grow all year round, and often it is necessary for researchers to undertake field-based studies to confirm this. Seasonal patterns of marine mollusc exploitation at a site, or between sites in a region, are usually established using a selected species as a proxy for the seasonality of all mollusc-gathering activities, but ideally more species should be used. The number of samples from final growth increments required to establish season of death of each shell also needs validating for each particular species, especially fast-growing species where accuracy is low if only one or two samples from the terminal growth stages are analyzed.

The potential for human foragers to impact their marine mollusc resource base is of considerable interest and debate. A decrease in the size of shells over time in archaeological deposits can be attributed to predation pressure from human foragers, provided other environmental causes can be discounted. Some recent studies have shown increases in the size of certain species of exploited molluscs, and although the reasons invoked for this are varied, they demonstrate that different outcomes can arise in particular multifactorial ecological and cultural contexts. Even if human foragers periodically depleted a mollusc species, there is no reason to suppose they caused even local extinction. Past human foragers must have been ecologically knowledgeable, because their livelihoods depended on it, and they would have devised strategies to cope with resource depletion, such as switching to alternative resources, or foraging at localities where resources were not depleted. Such strategies serve as a means of resource management. Perhaps the most sophisticated way to manage shellfish resources is by some form of “cultivation.” Mussels (*Mytilus californianus*) from a rock shelter in coastal northern California appear to have been harvested intensively at intervals of around 24 months, allowing a “fallow” period for the populations to recover. More sophisticated still are Late Holocene “clam gardens,” intertidal stone-walled terraces in British Columbia, Canada, constructed to create optimal growing conditions for high-density “cultivation” of clams. For further discussion of seasonality and of marine molluscs as human resources, with references to key literature, see Thomas (2015b).

Mollusc shells have long been used for decorative and utilitarian purposes. They show great diversity of size, shape, robustness, and so on, which affect the manufacture, use, and performance of shell tools, and the technological choices shell-workers have to make. The degrees of modification of shells to produce artifacts and the levels of technology required are highly variable, depending upon skill, the equipment available, the physical properties of the shells being exploited, and the types of artifacts required. Sometimes virtually no modification is needed; for example, scaphopod molluscs have natural holes at each end of their tubular shells, making them “natural” beads. Unmodified mollusc shells can be used as tools and, unless modified by wear during use, this use might be undetectable; see Szabó (2013) for the identification of shell use. Investigations of the use of shell tools are patchily represented in the literature. A use-wear analysis of Upper Paleolithic shell tools from a cave in northern Spain showed they had been used for a range of procedures, including the processing of red pigments (used for cave wall painting) and the treatment of animal hides. Studies of residues resulted in the identification of starch granules (see STARCH GRANULE ANALYSIS) on shell tools in Polynesia, providing evidence of processing of local crop plants and of the specific uses of the shell tools themselves. Marine mollusc shells have also been used in a range of other ways, such as crushed in mortar, and other products have been extracted from molluscs, most notably dyes (see DYES) from various species of gastropods.

The linkages between personal ornaments and the origins of modern human cognitive behavioral traits such as symbolism have been highlighted in recent years. Some of the earliest known examples are of the bivalve *Glycymeris* associated with pieces of red ochre in Middle Paleolithic contexts in Qafzeh Cave, Israel, 92,000 years ago. Very early shell beads with clear evidence of deliberate perforation occur in Middle Stone Age deposits at Blombos Cave, South Africa, from 76,000 years ago. Neanderthals may have used shells as pigment containers, ornaments, and tools such as scrapers, even before modern humans had evolved.

Shells from sites outside the natural geographic distribution of mollusc species provide evidence for provenience and exchange. Long-range connections across at least 1,000 km have been inferred from artificially perforated marine shells of Mediterranean origin from an Upper Paleolithic site in Germany. Analytical data are of increasing value for determining provenience. Artifacts from the marine bivalve *Spondylus gaederopus* are widely distributed across Neolithic Europe, and oxygen ($\delta^{18}\text{O}$) and strontium ($^{87}\text{Sr}/^{86}\text{Sr}$) isotope analyses reveal the Aegean or Adriatic, rather than Black Sea, origin of these shells.

Scientific studies of marine molluscs allow archaeologists to investigate many aspects of past human behavior. Recent innovations have extended the range of questions that can be investigated, with increased output of high-quality research. This trend looks set to continue, carried forward by the many young scholars entering this exciting field.

SEE ALSO: Mobility and Oxygen Isotopes;
Sea-Level Change

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Oils and Fibers

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Remains of oil crops are regularly encountered during paleoethnobotanical (archaeobotanical) research (see PALEOETHNOBOTANY), those of fiber crops much less so. Such finds provide the scientific basis for this entry, which focuses on the use of these crops in Europe.

Both types of plant remains are relatively seldom found charred, which is the most common state of preservation encountered, and particularly relevant for the recovery of cereal remains. This strongly influences the observed distribution pattern of oil crop finds, and even more so of fiber plants. Waterlogged preservation is usually necessary for the recovery of fiber crops (apart from desiccated preservation which is restricted to arid regions and salt caves (see FORMATION PROCESSES)).

The use of oil-rich seeds considerably predates the introduction of agricultural practices in western Europe. Oil-rich hazelnuts were commonly gathered in hunter-gatherer societies following hazel's post-glacial spread into the region during the Boreal period (ca. 8000 BCE). With the introduction of agricultural knowledge in this area during the Early Neolithic Linearbandkeramik (LBK) culture (ca. 5300 BCE) (see DOMESTICATION), two cultivated crop plants with oil-rich seeds arrived on the scene: linseed/flax (*Linum usitatissimum*) and small-seeded opium poppy (*Papaver somniferum* var. *setigerum*).

Flax can be cultivated both for its oil-rich seeds and for its fibers. Both uses can result in finds of seed remains, but occasionally more information on the former use of this crop can be gained. The utilization of linseed oil is difficult to demonstrate by archaeobotanical means. The fact that in waterlogged material sometimes only the rims of the seeds are found might relate to the pressing of the seeds to extract oil, but digestion

(by people or livestock) has comparable effects. Herbig and Maier (2011) demonstrated significant differences in flax/linseed seed size which they linked to the use of the plants. Large-seeded specimens point to the use of the oil-rich seeds and small-seeded ones to the use of fibers (Figure 1).

Remarkably, whereas linseed belongs to the eight Neolithic founder crops domesticated within the fertile crescent in the Near East, this is not the case for opium poppy. Bakels (2009, 30) inferred a western Mediterranean origin for this crop and proposed that a "French connection" was involved in the spread of opium poppy to the Dutch and German LBK farmers.

Although the dataset is still patchy, flax seems to have maintained its status as a crop plant until the present day. Opium poppy, in contrast, vanished from the crop record during the Bronze Age, only erratically occurred during the Iron Age (800–12 BCE) and returned as the larger seeded var. *somniferum* during the Roman period. This again points to a Mediterranean connection, the vector being the Roman garrisons that were established over large parts of Europe.

In the Bronze Age, the range of oil crops grown was not enlarged, but during the Iron Age, two new species with oil-rich seeds were taken into cultivation, both belonging to the crucifer family. Most widespread was gold-of-pleasure (*Camelina sativa*), with turnip (*Brassica rapa*) of more local importance. The larger range of oil crops grown during the Iron Age coincides with the increase in other types of crops. This is most likely related to the much wider variety of soil types inhabited and used for cultivation, including wet environments like salt marshes and peats. In fact, gold-of-pleasure was the most common crop at the Dutch Early Iron Age site of Assendelft situated on a raised bog (Therkorn et al. 1984), being one of the very few crops suited for this extreme type of environment—just like the faunal main component at this site, sheep. In the estuary of the River Meuse, during this same period a specialization in oil crop cultivation seems to have taken place, with linseed and

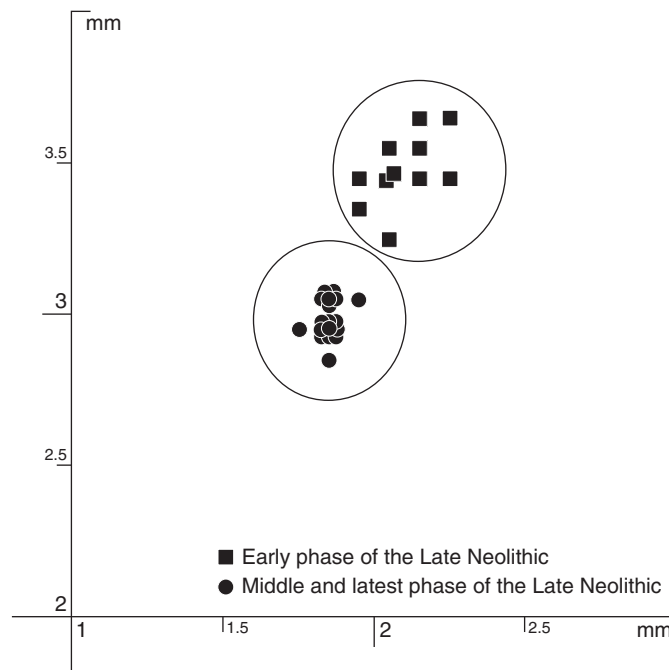


Figure 1 Dimensions (width and length) of flax seeds in lakeshore settlements at Lake Constance and in Upper Swabia. Two distinctive clusters show the large-seeded “Pfyn-type” flax in the early phase of the Late Neolithic and the small-seeded “Horgen-type” from the middle and latest phase of the Late Neolithic.

Source: Republished with permission from Springer, Herbig & Maier 2011.

gold-of-pleasure occurring on Spijkenisse 17–35 and turnip on Spijkenisse 17–30 (Brinkkemper 1993, 138).

In (proto-)historic times, the range of oil crops grown is supplemented by hemp (*Cannabis sativa*), which has a dual purpose just like flax, as it can be grown for both fiber and its oil-rich seeds. In several countries, the Roman occupation seems to have led to the spread of this crop into new areas. The common occurrence of hemp seeds in medieval cesspits clearly evidences seed consumption. Black mustard (*Brassica nigra*) became common during the Roman period and even more so in medieval cesspits. This crop weed might have been purposefully collected, or even cultivated, for its tasty seeds.

Major plant oils from other parts of the world include coconut, cottonseed, olive (see OLIVES AND OLIVE OIL), palm, peanut, safflower, sesame, soybean, and sunflower. In addition, a long list of plants were used to produce oil, but on a much smaller scale, and usually with greater difficulty.

Remains of all of the main oil plants have been found in archaeological contexts, and the use of their plant oils is likely.

Just as with oil-rich seeds, fibers were being used by humans from an early date. The use of bast fibers from the phloem of certain trees, especially lime (*Tilia* sp.) and elm (*Ulmus* sp.), in the production of ropes and nets was already known to Mesolithic hunter-gatherers. In several Neolithic contexts (ca. 5500–2000 BCE) throughout Europe, flax fibers (linen) have been recorded, clearly evidencing their use in textile production. The Swiss lake-side settlements with their waterlogged preservation conditions produced a wealth of plant (and animal!) fiber products. In an overview of Neolithic and Bronze Age fibers from these sites, Rast-Eicher and Dietrich (2015) recorded oak, lime, and willow bast, in addition to the fibers from cultivated flax. For the production of linen from flax stems, retting is required. Retting is a process involving microorganisms and moisture on plants to rot

away much of the cellular tissues surrounding plant fiber bundles, to facilitate separation of the fiber from the stem. Retting can be done either in water or by means of dew on land.

This odorous activity leaves recognizable traces, as is demonstrated by the combination of pollen and macro-remains in medieval pits in the Netherlands (Pals and Van Dierendonck 1988). Vice versa, the demonstration of flax retting implies the production of linen. In China, where linseed has been used for over 2,000 years, the use of flax for fiber appears to have started only in the last century (Liu et al. 2011).

Hemp probably originates from eastern Asia, where it was used for rope, clothing, sails, and bowstrings by 6200 BCE (Warf 2014). Whereas flax fibers have occasionally been recorded in archaeological sites, finds of hemp fiber are very rare. During pre- and proto-historic times, other noncultivated plants are likely to have been used for fiber production. Nettle seeds (*Urtica* sp.) in particular, are almost ubiquitous in the archaeological record and occasional finds of nettle fiber are known. Desiccated remains of baskets, regularly found in Egypt, demonstrate that leaves and leave-sheets of palms and leaves of grasses were used for a variety of products, from donkey saddles to containers and brooms, with only minimal processing required (Wendrich 1999).

Other fiber crops include cotton, jute, ramie, sisal, and coconut, with only a few plant families involved—Malvaceae (cotton, jute), Agavaceae (sisal), and Urticaceae (ramie). It is only in relatively recent times that use of these tropical fibers became a feature of the European economy.

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Olives and Olive Oil

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Olive (*Olea europaea* L.) is an oil-rich fruit, native to the Mediterranean/Near East, which usually is cured by fermentation in solution with brine, lye, or salt to remove bitter phenols before eating. Pressed olive fruits produce oil which can be used for cooking, lighting, or as a base to medicinal/hygienic products such as ointments, perfumes, and soaps. Cultivated olive is one of the earliest domesticated fruits, most likely brought into cultivation shortly after cereal cultivation developed in the Fertile Crescent. Along with grapes (see GRAPES AND VITICULTURE) and wheat (see WHEAT), olives are a member of the Mediterranean triad (the suite of plants underpinning ancient agriculture in the region).

Despite substantial historical and archaeological information, there are fundamental gaps in our knowledge of cultivated olive and its wild progenitor(s). Debate about when and where olive oil processing first occurred and, indeed, if “table olives” were consumed prior to the Hellenistic period (e.g., comment in Kaniewski et al. 2012) is due, in part, to the lack of comprehensive data (by both regions and periods). Oleaculture suffers, especially, from being well documented in historic periods and, like cereals or grapes, is so ubiquitous to Mediterranean/Near Eastern agriculture as to be taken for granted. English-language reviews of oleaculture in Greece (Foxhall 2007) and North Africa (Mattingly 1996) provide a useful introduction to the socioeconomic value of olives to ancient Mediterranean societies, but we should remember that many of the cultures of the Mediterranean (e.g., the Phoenicians, early Minoans, Etruscans) are not as well documented.

There are approximately 40 evergreen tree/shrub taxa within the genus *Olea*, which subdivide into three subgenera: *Olea*, *Paniculatae*,

and *Tetrapilus*. Molecular dating from modern material (i.e., genetic generational sequences based on the mutation rate of nucleotide sequences of DNA—in this case plastid DNA and ITS-1 sequences—suggests that the genus *Olea* has an evolutionary history spanning the Tertiary (ca. 66–2.5 Ma) and genetic divisions between subgenera or sections coincide with major climatic events. In particular, diagnostic peltate plates surrounding (sometimes completely obscuring) leaf stomata are unique to *Olea* section *Olea* and may represent genetic adaption to desertification; this water-saving adaptation marks the separation of section *Olea* from section *Ligustroides* within the subgenus *Olea* at ca. 17.7 Ma (coinciding with the Mid-Miocene climatic optimum—Besnard et al. 2009).

The wild form of olive, known as oleaster (*Olea europaea* L. var. *sylvestris*), has existed since the Pleistocene (ca. 2.5 Ma to ca. 11,700 BP) and its fruit pits are indistinguishable from cultivated olive (*Olea europaea* L. var. *europaea*). Oleasters tend to be shrub-like, while cultivated or feral olives occur as trees. There are some potential differences between cultivated olive wood and wild oleaster wood (e.g., Terral and Arnold-Simard 1996); nevertheless, it is still considered problematic to distinguish wild from cultivated olive wood. Fossils and studies of olive charcoal/pollen from Middle–Upper Paleolithic sites in the Mediterranean suggest that oleaster survived the last glaciation in refugia. It is believed that the olive tree was brought into cultivation quite early in the Holocene from either the wild oleaster form or the true *Olea europaea* L. var. *europaea* form, but the precise timing and location(s) of this event are not yet known. By the third millennium BCE, olive trees were cultivated throughout the Mediterranean and Near East.

Olive pits are easily identified using conventional paleoethnobotanical methods (see PALEOETHNOBOTANY) relying on low-power microscopy. Archaeologically, olives are encountered most frequently as charred plant remains

(pits or charred wood), but also occur through other modes of preservation (desiccation, mineralization, and/or waterlogging). “Table olives” are less likely to occur as charred remains because their processing does not directly involve heating; conversely, the by-product of oil production is likely to be preserved through charring, since olive processing residue (hereafter OPR) is used traditionally as a fuel in the region (e.g., Rowan 2015; Warnock 2007). Olive pits are easily recognized, with their distinctive elliptical shape, pointed apices, and irregularly veined or furrowed surface; however, their morphology can be highly variable (i.e., ranging from elliptical to rounded and/or they do not always have deep veins/furrows).

In areas where morphologically similar fruit pits occur, identification of olive pits can be problematic. For example, in Egypt paleoethnobotanical identification of olive requires caution because there is a marked overlap between sub-rounded *nabq* (*Zizyphus spina-christi* L.) pits and subelliptical olive pits, which can only be resolved by opening whole pits or examining broken fragments to determine if one chamber for the kernel (indicating *Olea europaea*) or two separate chambers (indicating *Zizyphus spina-christi*) are present. This is especially relevant to highly fragmented remains, where it is not always possible to fully reconstruct overall shape or determine if one or two chambers are present.

Olive pit dimensions also are variable, which suggests there is potential to distinguish varieties of “table” or “eating” olives from “oil production” olives. Although many conventional paleoethnobotanical studies record the dimensions of olive pits, the effect periods of drought may have on the formation of olive pits is not understood. Certainly control of archaeological context is essential if dimensions are recorded, since many deposits (i.e., fills of pits, cesspits, ditches, etc.) are likely to represent several years of different harvests, rather than a single event. The application of computer recognition programs based on fractal geometry (Bari et al. 2003) to describe the dimensions of olive pits, including the extent/degree of furrowing, have potential and may better resolve differences between “table” and “oil” olives and, possibly, varieties within each category. The effect of drought on the size and/or viability of olive pits is a moot point since propagation of olive trees

is achieved through vegetative cuttings, layers, or grafting; therefore, successful germination of “seed” is irrelevant. In essence, current olive varieties are effectively clones of early domesticated olive trees.

Paleoethnobotanical evidence for the use of OPR as fuel is known from several Mediterranean sites (e.g., Rowan 2015). The significance of angular versus rounded fractures (or breaks) in ancient olive pit fragments remains debatable. Recent work (e.g., Braadbaart, Marinova, and Sarpaki 2016) suggests that there is no reason to presume sharp angular fractures on olive pits are *not* ancient, since freshly pressed, modern OPR exhibits similar fractures; however, others have noted that rounded edges on fractures are characteristic of some archaeological OPR assemblages, and that taphonomic reasons, excavation methods, or mechanical action during flotation may explain this (e.g., Rowan 2015, 467 and footnote 24). Scanning electron microscopy and reflectance analysis of charred OPR potentially can provide information on firing temperature and/or identification of intentional charring of OPR to form charcoal fuel (Braadbaart et al. 2016).

Although olive trees can produce a crop as early as seven years after planting, trees do not reach full fruit-production maturity before at least two decades and, therefore, the decision to plant olives probably is best viewed as “planting for the next generation.” Conversely, the destruction of olive orchards would set back oleoculture in a region by at least a decade, if not two. The tendency for the production of olive oil to be a communal activity where regional harvests are both processed and pooled together, often at a central mill installation, will somewhat mitigate against variable harvests.

It is likely that Roman olive orchards represented the greatest extent of oleoculture in the ancient world (e.g., Foxhall 2007; Mattingly 1996); however, the precise limits of ancient oleoculture are currently only a matter of conjecture. In places like North Africa and the Near East, where desert conditions prevail and vegetation is less likely to obscure features, application of space-based light detection and ranging (LiDAR) could potentially reveal field systems. Certainly, Mattingly (1996, 226–228) suggests that Roman olive tree planting pits were visible in parts of Italy

and Tunisia where, shortly after World War II, aerial photography detected grids of rectilinear pits. Although cultivated and wild forms of olive pollen are indistinguishable, pollen can be identified securely to the genus *Olea* and there have been a number of palynological studies which link a substantial increase in *Olea* pollen to the introduction of large-scale olive orchards (e.g., Kaniewski et al. 2012 for Syria).

Olive wood charcoal can be problematic for reliable radiocarbon determination because olives trees are so long-lived (typically 200–300 years, although older examples are known). As a result, charcoal samples for radiocarbon determination should be based on roundwood fragments representing < 15–20 years growth. The Mediterranean/Near East is known for limited woodland and it is likely ancient societies would have been pragmatic in their selection of wood for timber and fuel, presumably dismantling and re-using timbers from structures, such as ships, for architectural and decorative wooden elements or for fuel; therefore, radiocarbon determinations from olive wood/charcoal should be treated with extreme caution, especially if not from roundwood with a known number of growth rings.

The specific identification of olive oil (i.e., as a residue on or within pottery vessels/lamps) remains problematic. Oleic acid is a diagnostic monounsaturated fatty acid in olive oil, but can be found in other plant and animal oils; moreover, unsaturated fatty acids are highly reactive, especially when exposed to water (fatty acids are water soluble and hydrolysis can break down more complex glycerides, freeing fatty acids). Recent methodological research on modern and archaeological fats using gas chromatography combustion isotope ratio mass spectrometry (GC-C-IRMS) (see GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS)) has firmly established that in areas where plant oils (such as olive oil) were in use, it is not possible to securely distinguish them from porcine/ruminant adipose fats by comparing the ratio of $\Delta^{13}\text{C}$ to $\delta^{13}\text{C}_{16:0}$ (Steele, Stern, and Stott 2010).

SEE ALSO: Paleoethnobotany and Stable Isotopes

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Organic Residue Analysis

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Organic residue analysis is the investigation of organic remains using instrumental analytical chemical/biochemical techniques. Such highly selective and sensitive techniques are required because the organic remains are either *amorphous*, for example fat and wax deposits, tars, pitches, or bituminous materials, or *invisible* due to their presence in complex matrices, such as surface or absorbed residues in pottery, human, or animal remains, soils/sediments, or stone objects; the components of organic residues are usually present at *trace* concentrations.

In organic residue analysis, deriving information relating to human activity in the past rests on the identification of archaeological *biomarkers*, that is, substances and biochemical compounds occurring in organic residues that can be directly related to the animals and plants humans exploited to fulfil a wide range of activities and requirements (diet, medicinal, technological, ritual, etc.) The biomarker approach relies upon matching the structures of compounds or mixtures of compounds, the latter termed “distributions,” “chemical fingerprints,” or “chemical signatures,” surviving in organic residues to the compounds and mixtures known to exist in living organisms likely to have been exploited in the past. Investigations performed since the 1970s have confirmed the survival of a wide range of compound classes at archaeological sites in association with various archaeological artifacts, biofacts, and deposits. These include lipids, proteins, DNA, and pigments, but rarely carbohydrates (although starch grains (see STARCH GRANULE ANALYSIS) are frequently reported microscopically they have yet to be chemically characterized). In the cases of ancient DNA and proteins the entire structure of the original biopolymer will rarely, if ever, survive

intact, so the structurally diagnostic biomarker entity will be fragments (sequences of DNA or building blocks and amino acids or peptides, respectively). In contrast, under favorable conditions, many small molecules, such as lipids—that is, the organic solvent soluble components of living organisms—are preserved unchanged or with minor structural alterations, making them the main targets in organic residue analysis.

Organic residue analysis requires analytical techniques able to achieve molecular-level resolution and identification. Organic materials encountered at archaeological sites are complex mixtures of biochemical components. This complexity is increased further through human activity, such as mixing biological materials, for example in food preparation, and through compositional alterations wrought by decay during burial (see TAPHONOMY). The resolution and identification of molecular structures in such mixtures demands the use of chromatographic (gas chromatography (GC) (see CHROMATOGRAPHY AND ARCHAEOLOGICAL MATERIALS ANALYSIS) and high performance liquid chromatography (HPLC) (see HIGH PERFORMANCE LIQUID CHROMATOGRAPHY (HPLC)) and mass spectrometric (MS) methods; hence, the emergence of organic residue analysis has been strongly tied to advances in instrumental methods in the modern era.

The assignment of a specific source or constituent of an organic residue based on the presence of a particular biomarker component or mixture of components demands a high degree of analytical rigor. The structures of biomarkers must be rigorously determined. Sometimes the structure of a single biomarker component is sufficient to define the origin of a constituent of an organic residue, but, more commonly, a mixture of biomarkers is used to provide chemotaxonomic-based assignments. Degradation of the components of organic residues commonly removes diagnostic compounds, leaving undiagnostic compounds or distributions, and interpretations have thus to be made with great caution and complementary information sought. Stable isotope compositions,

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notably carbon ($^{13}\text{C}/^{12}\text{C}$), hydrogen ($^2\text{H}/^1\text{H}$), and nitrogen ($^{15}\text{N}/^{14}\text{N}$) isotopes, are becoming increasingly used (the latter only in the case of amino acids), providing access to information often unavailable through the structures of the compounds alone, notably metabolic and/or environmental information. The combination of molecular structures and their stable isotope compositions is most powerful in the case of the ubiquitous fatty acids that make up all fats and oils and the amino acids that comprise all proteins.

A critical aspect of organic residue analysis is consideration of the archaeological and paleoecological context. In practice, consideration of geographical location, time period, and zooarchaeological (see ZOOARCHAEOLOGY) and paleobotanical (see PALEOETHNOBOTANY) evidence can help to simplify interpretations by constraining the range of potential sources of observed biomarkers and increase the diagnostic potential of seemingly rather undiagnostic biomarkers. Further information is recorded in the makeup of organic residues in the form of altered chemical components, since certain structural transformations are predictable, thereby recording the life histories of residues derived from different technological activities or burial transformations. Thermal histories of organic residues, for example wood tar/pitch or heated animal fats/oils, are commonly recorded in the structures of specific chemical components. Often the precursor compounds are too unstable to survive over archaeological time due to their susceptibility to degradation.

All scientific investigations require experimentation to test hypotheses and support interpretations. Thus, experimental studies are an indispensable, but sometimes underused, aspect of investigations of organic residues. Experimental approaches have been applied in relation to vessel use, heating of bones and seeds, burial of pots and bones, feeding animals on controlled diet as analogs for past human diet, agricultural experiments, and sampling organisms from defined feeding experiments or modern ecosystems to provide reference databases (Evershed 2008, 2009).

Organic residues have been most widely studied in archaeological pottery, where they survive in (1) actual contents preserved in situ as vessel fills, (2) surface residues appearing as visible

residues on the exterior or interior of vessels, and (3) absorbed residues preserved within the vessel wall, invisible to the naked eye. Vessel fills are very rare, the most notable being the contents of canopic jars. Organic residues occurring on the exterior surfaces of vessels correspond to either sooting, derived from heating on a fire, or rather rare instances of applied decorations. Interior residues are often carbonized, and presumed to be residues of “cooking” failures, while visible residues in lamps can represent the remains of the fuels and wicks. Post-firing treatments are also seen, particularly as copious linings associated with Roman amphorae, presumed to have been applied to seal vessels. Visible residues have been chemically investigated and are widely used in dating programs (see DATING IN ARCHAEOLOGY and RADIOCARBON CALIBRATION AND AGE ESTIMATION), although they can become affected by post-burial or post-excavation contamination due to their exposed nature. Absorbed organic residues are the most widely studied category, since they are present in the vast majority of pottery assemblages, survive over long timescales, are protected by the ceramic fabric, and provided an integrated record of vessel use.

Biomarker investigations of organic residues in pottery date to the 1970s when the ability of clay to absorb lipids from foodstuffs processed in vessels was recognized. The results of GC/MS (see GAS CHROMATOGRAPHY-MASS SPECTROMETRY (GC-MS)) analyses of solvent extracts of powered potsherds have become the preferred approach to organic residue analysis of pottery. The introduction of GC combustion isotope ratio MS (GC-C-IRMS) in the early 1990s allowed the isotopic composition of individual compounds from archaeological extracts to be determined, which has significantly extended the utility of organic residue analysis. Studies relating to vessel use have employed replica vessels, ceramic chips, and powder to investigate both physical and chemical phenomena relating to organic residue deposition and transformations. Pottery made today provides insights into the impacts of long-term vessel use that cannot be addressed in laboratory experiments. Potsherds impregnated with organic residues have provided substrates for investigating the impacts of burial on chemical and stable isotopic compositions.

GC/MS of organic residues has revealed a wide range of biomarkers which have led to the identification of residues of an impressive range of commodities from around the world. Resins and tars have been identified through the detection of characteristic di- and triterpenes, enabling their sources to be pinpointed to tree species. The signature of beeswax consists of a complex suite of lipids, including *n*-alkanes, *n*-alkanoic acids, and alkyl (hydroxy)palmitate monoesters. Triacylglycerols (the building blocks of fats) and unsaturated fatty acids are prone to degradation, so animal fats are recognized by their saturated fatty acids. Further identification of animal fats to their source is possible using their stable carbon isotopic compositions ($\delta^{13}\text{C}$ values), enabling ruminant and nonruminant fats, and adipose and dairy fats to be distinguished. Plant-derived oils and waxes are identified based on wax esters, long-chain *n*-alkanes, *n*-alkanols, and even-numbered fatty acids. As polyunsaturated fatty acids common in fresh aquatic resources are degraded through vessel use and diagenesis, fatty acid degradation products, including vicinal dihydroxy acids, ω -(*o*-alkylphenyl)alkanoic acids, and isoprenoidal fatty acids are preferred biomarkers for identifying the organic residues of aquatic resources (e.g., fish oils).

While there was an early recognition that the analysis of lipids extracted from single vessels was a powerful method for defining pottery use, subsequent developments have seen an increase in the scale of studies, with typically tens to hundreds of potsherds from ceramic assemblages being investigated. Such studies allow subsistence practices to be unravelled at the regional, local, and even household levels and chronological trends in exploitation of resources to be explored. Paleoenviromental information can be obtained through the determination of carbon and hydrogen isotopic composition of fatty acids. Technologies involved in the production of ceramic vessels, including manufacture, finishing (e.g., sealing or decoration), and repair, can also be identified through lipid residue analyses.

The capacity to distinguish different animal fats preserved in organic residues in pottery allows the procurement and consumption of animal products to be investigated (see **FOOD RESIDUE ANALYSIS**). Questions relating to the exploitation of domestic animals for meat or milk

have been widely investigated in Europe, Eurasia, and Africa. Evidence of dairying (see **DAIRYING**) has been found in the seventh millennium BCE in northwest Anatolia, while perforated vessels from Central Europe demonstrate that cheese-making was practiced in the sixth millennium BCE. The consumption of aquatic resources has been extensively investigated, notably in Japan, where lipids from aquatic organisms have been extracted from pottery dating to 13,000 BCE.

Under favorable circumstances, lipid biomarkers have been shown to survive in soils and sediments (Bull and Evershed 2012). A critical requirement is that the deposits must have remained undisturbed by significant bioturbation from burrowing animals or human disturbance, such as plowing. Sealed tomb sediments and cave deposits with clear stratigraphies offer opportunities to study chronological changes in biomarker compositions with time. In this respect, the approaches are strongly aligned with the molecular stratigraphic principles of organic geochemistry. Indeed, investigations of lipid biomarker sediments at early hominin sites have been used for paleoenvironmental reconstructions (see **PALEOENVIRONMENTAL RECONSTRUCTION**).

Biomarker analyses of more recent archaeological sediments have provided insights into anthropogenic inputs, reflecting a range of human activities, for example waste disposal, fertilization of agricultural land, and ritual/funerary activities in tombs. An early study in the 1980s of the chemical components of sediments from a Roman fortification ditch at the Antonine Wall in Bearsden, Scotland showed high concentrations of deoxycholic acid (and 5 β -stanols) in one horizon, suggesting the ditch had been used as a drainage channel for a latrine (Knights et al. 1983). The wider utility of the approach has been demonstrated through investigations of fecal biomarkers in a range of other waste deposits. This stimulated development of the approach; building databases of biomarker 5 β -stanol and bile acid compositions of modern animals revealed the possibility for systematic identifications of the species origins of fecal deposits. Studies of soils from experimental archaeological and agricultural sites have provided important tests of the utility of steroidal biomarkers. The recognition by early pastoralists

that improved crop yields could be achieved by the use of fertilizers would have been a major step forward in the development of agriculture. Under favorable circumstances, the biomarker signals appear to be sufficiently long-lived to provide assessments of manuring practices and ancient agricultural systems ranging from the northern isles of Scotland to the Mediterranean, revealing the use of manure as fertilizer. The value of these biomarker approaches has been recognized in the study of coprolites (see COPROLITES) to provide a novel source of paleobiological and paleoecological information.

Tomb and cave sediments offer opportunities to reconstruct anthropogenic activities through the biomarkers they contain. The poor morphological preservation of organic materials in a Bronze Age tomb in Syria meant that mapping funerary activities rested significantly on sediment biomarker distributions. Remarkably, solvent extracts of sediments from a number of areas of the tomb were vivid purple in color. HPLC (see HIGH PERFORMANCE LIQUID CHROMATOGRAPHY (HPLC)), MS (see MASS SPECTROMETRY (MS)), and nuclear magnetic resonance (NMR) (see NUCLEAR MAGNETIC RESONANCE (NMR)) spectroscopy confirmed the presence of brominated derivatives of indigo and indirubin characteristic of the renowned Tyrian or Royal Purple deriving from decayed textiles, which had become incorporated into the sediments (James et al. 2009).

Organic residue analysis is undertaken on a range of human and animal remains to provide insights into biomolecular preservation, funerary practices, and ancient diet. While soft tissues rarely survive, where they do preserve (e.g., in waterlogged, desiccated, or frozen bodies) they attract a high level of interest. Early studies of lipids in bog bodies demonstrated a high level of indigeneity that was important in establishing the potential of lipid biomarkers in buried archaeological artifacts and biofacts. Beyond this, lipids offer an alternative target to proteins for radiocarbon and/or stable isotope analysis. Biomarker analyses have revealed components of bacteria involved in degradation, while the presence of mycolic acids holds potential for detecting pathogenic infections (Minnikin et al. 2012).

Skeletal remains are without question the most widely occurring class of human and animal

remains, with stable isotope and/or radiocarbon analysis routinely performed on purified collagen. This is not generally considered to fall into the area of organic residue analysis. However, there are areas where there are resonances with organic residue analysis, notably when the stable isotope compositions of individual amino acids and lipids from skeletal remains offer opportunities for refining dietary interpretations in human and other animals (Evershed 2009). The application of proteomics approaches employing MS analysis of tryptic digests to identify highly fragmented bone is a notable case where peptide sequences are the biomarker (Buckley et al. 2009).

The copious organic balms (see EMBALMING) applied to many Egyptian mummies to preserve the corpse are amorphous in nature and require the use of organic residue analysis techniques to characterize their components and offer insights into why the ancient embalmers chose specific natural products for their preservative properties or symbolic significance. The balms can be highly complex, comprising mixtures of biomarkers characteristic of coniferous (diterpenoids) and pistacia (triterpenoids) resins, beeswax, plant oils, animal fats, and so on. One of the balm components that has attracted considerable attention is natural asphalt (also referred to as petroleum bitumen). GC/MS “fingerprints” of the sterane and triterpene hydrocarbons have been used to trace the source of the bitumens to a range of sources in the Middle East, with the famous Dead Sea floating blocks being particularly prominent (Connan 1999).

Plant remains mainly survive at archaeological sites as carbonized remains. Chemical investigations have shown that carbonization destroys biomolecular integrity. However, intact biomolecules preserved in desiccated and waterlogged remains have provided insights into diagenetic processes associated with long-term burial. Carbonized cereals retain carbon and nitrogen isotope signal of manuring and irrigation regimes within their thermal altered structure, although the chemical environments within the seeds are undefined in any molecular sense. DNA in plant remains preserved under normal temperature conditions have been used in genetic studies, while lipids have found value

as comparative materials for use in the interpretation of organic residues from pottery recovered from the same sites.

The biomarker analyses discussed above fall under the heading of “targeted” analyses, since the materials are well understood and established protocols exist for the analysis of specific classes of biomarker. A range of other amorphous organic remains are preserved at archaeological sites including lumps of fat, tar, pitch, bitumen, resin, contents of glass and metal containers, deposits on stone tools, and funerary residues. Their analyses require a more classical approach involving solubility assessments, elemental analysis, and spectroscopy, among others to establish the bulk properties of the materials, revealing whether they are organic or inorganic, polymerized, and so on. Once established, appropriate analytical protocols can be designed to determine their comprehensive chemical compositions. A rare such example was a Roman tin container with its tightly fitting lid and contents, a “cream” in place. Characterization of the cream required the use of elemental analysis, loss on ignition, GC, GC/MS, pyrolysis GC/MS, GC-C-IRMS, Fourier transform infrared (FTIR) spectroscopy, iodine test, X-ray diffraction, and X-ray fluorescence to achieve a “total” analysis, revealing a mixture of animal fat and purified starch as the base for the white tin pigment cassiterite (SnO_2) (Evershed et al. 2004). The “cream” was probably a cosmetic (see PERFUMES AND COSMETICS) skin whitener.

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Ostracods and Cladocerans

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Ostracods and cladocerans are powerful tools for reconstructing past environments because of their sensitivity to environmental change. They are of particular value in understanding the history of aquatic systems manipulated by humans. Irrigation canals, reservoirs, and mill ponds or mires offer a unique opportunity to study these groups to identify the human–environment interaction. Distinction of anthropogenic from climatic signatures is critical to recognize environmental impact over time.

These aquatic forms are known as seed shrimps (ostracods) and water fleas (cladocerans), respectively. The former thrive in marine and nonmarine realms, whereas the latter are mainly restricted to freshwater (they are rarely found in salt water). In nonmarine environments ostracods are represented by the Order Podocopida (suborders Cypridocopida and Cytherocopida); therefore, this entry focuses on this group in order to aid comparison with the Order Diplostraca (suborder Cladocera). A summary of the biological, morphological, and taxonomic characteristics is given below.

Ostracods

Ostracods are microscopic crustaceans ranging in size from 0.5 to 2 mm; some may be as large as 8 mm (Figure 1). Unlike other crustaceans, they are protected by a bivalve carapace made of low-magnesium calcite (calcium carbonate). The soft body consists of reduced trunk segmentation with five to eight pairs of limbs (appendages) that they use for crawling, swimming, mating (if amphigonic: female/male; some are parthenogenetic: somatic asexual reproduction), or grabbing food from

the surrounding environment. One of the oldest and most diverse groups of crustaceans, a conservative estimate suggests there are more than 20,000 living species, 8,000 of which have been described. Known since the Ordovician (500 million years ago), ostracods may include more than 65,000 living and fossil forms. Only the hard parts (valves) survive in the archaeological record.

Nine molting stages (ecdysis) allow the organism to shed its old carapace or shell before forming a new one. Genetic make-up and the environment both influence shell morphology and ornamentation. The shells have a bean-like shape that may vary from kidney-shape, to subrectangular, subtrapezoidal, or triangular. Secreted by the epidermis, the calcium carbonate shell incorporates more than 25 minor and trace elements into the calcite structure (Bodergat 1985). Surface ornamentation may be smooth to reticulated, striated, punctuated, with or without visible pore canals, simple, or cribrated. Genders are clearly dimorphic if the species is amphigonic.

Nonmarine ostracods are sensitive to water chemistry, salinity, temperature, and dissolved oxygen, among other parameters. They occur in freshwater, brackish, and brine conditions in lakes, ponds, wetlands, springs, and streams, including irrigation canals and reservoirs (Palacios-Fest 2002). Altitude and latitude are also important factors controlling the species' geographic distribution. Based upon their ecological requirements, it is possible to use this group in paleoecological reconstructions to understand the human–environment interaction. The reader is encouraged to consult Horne, Cohen, and Martens (2002) for further details on ostracod anatomy and ecology.

Cladocerans

The Cladocera include four infra-orders—Anomopoda, Ctenopoda, Onychopoda, and Haplopoda (according to the Integrated Taxonomic Information System: www.itis.gov). To date, about 620 taxa are estimated to represent the

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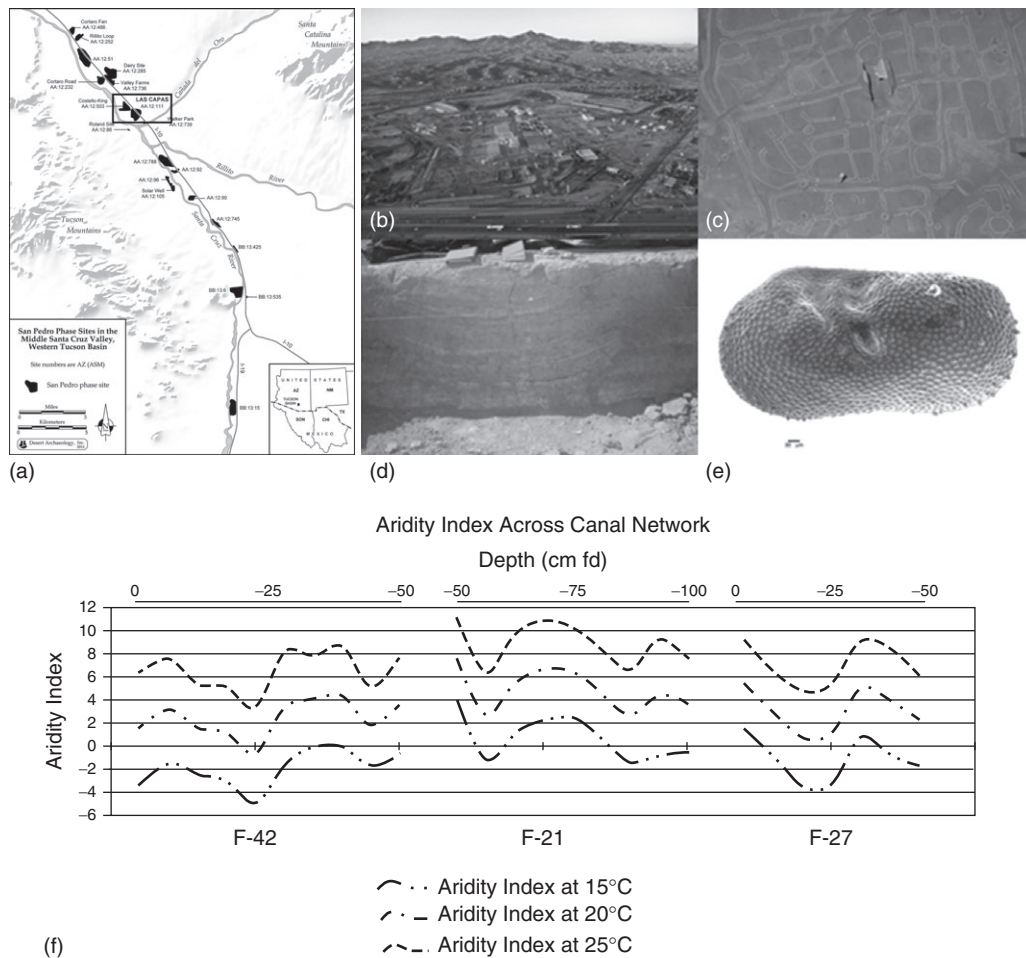


Figure 1 Las Capas archaeological site (AZ AA:12:111/753 (ASM)), Tucson, Arizona, the United States—a 3000-year-old irrigation canal network. (a) Location map; (b) general view of Tucson Waste Water Treatment Plant at Ina Road and Interstate 10; (c) canal network; (d) canal stratigraphy; (e) SEM image of *Ilyocypris bradyi*; (f) aridity index diagram showing three trends of aridification during canal operation assuming water temperatures ranged from 15 to 25 °C.

Source: Map and aerial photographs courtesy of Henry Wallace and Desert Archaeology, Inc.; other images property of MRPF.

Cladocera, in sharp contrast to ostracod diversity. Extant since the Paleozoic, the fossil record is better documented from the Mid-Mesozoic to the present (Kittel et al. 2014).

Cladocerans are microcrustaceans. They range in size from 0.2 to 6 mm and up to 18 mm (Forró et al. 2008) (Figure 2). The soft body is encapsulated within the secreted bivalve shell folded in half, made of lipids, slimes, chitin, and pigments that may uptake some minor

and trace elements like phosphorus, calcium, strontium, sodium, and iron (Smirnov 2014). Like other arthropods, cladocerans grow by molting their exoskeleton up to seven times or less (two for chydrids) (Dodson and Frey 2001). Even though sexual reproduction may occasionally occur, they are mostly parthenogenetic; this is known as cyclical parthenogenesis. Environmental parameters play a role in controlling species abundance and distribution.

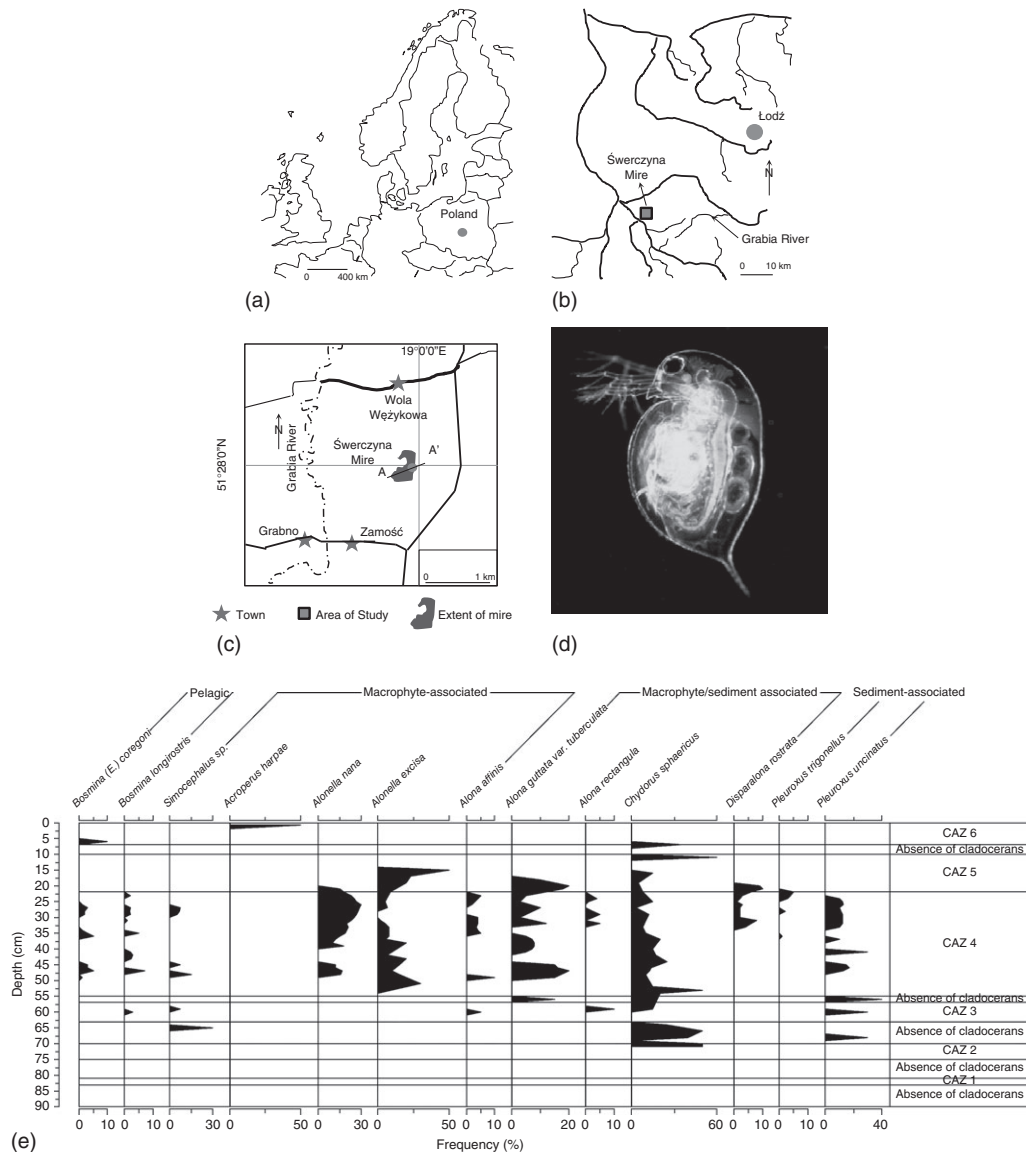


Figure 2 Świerczyna mire in the Grabia River valley, central Poland—paleoecology. (a) General location map; (b) site location map; (c) archaeological sites (triangles) and geological cross-section (A–A'); (d) *Daphnia pulex*; (e) cladoceran chronostratigraphy.

Source: Modified from Pawlowski et al. 2015; *D. pulex* images from bettatrading.com.au.

Some species are eurytopic (found in a wide range of environmental conditions), while others are stenotopic (found in restricted environments). The group occurs in lakes, ponds, and artificial mill ponds where slow-flowing waters prevail. They are also found in fast-flowing systems (Kittel et al. 2014). An important component of

the trophic chain, cladoceran populations are affected more by the presence of phytoplankton and predators than by water chemistry, salinity, or temperature, even though the latter appears to influence body size and reproduction. Most species form part of the zooplankton living in open water. Other species are nektonic, thriving

in bottom vegetation. For a detailed description of this group the reader is encouraged to consult Dodson and Frey (2001).

Like ostracods, cladocerans can be used to reconstruct past environments associated with human activity (see PALEOENVIRONMENTAL RECONSTRUCTION). Among the most useful approaches is the identification of lake status, such as climate changes, trophic oscillations, acidification, and water-level changes.

Sample preparation

Ostracods and cladocerans require different sample preparation procedures. As ostracods possess a hard calcium carbonate shell, extracting them from the sediments is somewhat easier than extracting cladoceran chitinous shell from the same materials. Ostracods may be removed from sediments through a simple procedure that consists of disaggregating the sediments in boiling soapy water, washing through a gentle shower, and letting the sample air-dry to allow the valves to be picked out with a fine brush using a low-power microscope (Palacios-Fest 1994).

Cladoceran chitin is quite resistant to many chemicals (except acetolysis); therefore, it is possible to follow similar procedures to those used in pollen analysis (Frey 1986, 669–675). Cladocerans can be extracted from samples examined for other biological remains such as plant macrofossils and insects (see SAMPLING IN ENVIRONMENTAL STUDIES). A compound light binocular microscope is used for sample examination. The slides contain not only complete exoskeletons but also their fragments, mainly resulting from predation or decomposition in situ. As in pollen analysis, it is convenient to prepare reference collections of whole organisms and their shells to compare with unknown specimens.

Quantitative analysis is necessary for both ostracods and cladocerans in order to reconstruct past environments. Total and relative abundances and species diversity are recorded. If possible, it is also important to record the taphonomic parameters (e.g., fragmentation, abrasion, disarticulation (for ostracods), and adulthood ratios).

Case studies

Las Capas archaeological site (AZ AA:12:111 (ASM)) and its associated canals (site AZ AA:12:753 (ASM)) offer the first refined reconstruction of a complex irrigation canal network operating during the San Pedro phase of the Early Agricultural period (1200 BCE–50 CE). The site is located along the Santa Cruz River in Tucson, Arizona, the United States. Geochemical data, stable isotopes ($\delta^{18}\text{O}$ and $\delta^{13}\text{C}$), and trace element molar ratios (Mg/Ca_v and Sr/Ca_v) were obtained from the valves of *Ilyocypris bradyi*, the most common and abundant ostracod in the canal network. The signatures obtained provided a unique record of ancient irrigation networks that allowed us to infer water-use patterns and how humans impacted the environment 3,000 years ago (Palacios-Fest 1994, 2002).

Water evaporation from the Santa Cruz River to the agricultural fields was tracked. Three trends were estimated assuming water temperatures ranged between 15 and 25 °C (Figure 1). Feature 42, the main canal, showed the lowest evaporation values. Feature 21, a distribution canal, displayed a slight increase in the aridity index observed at any given temperature. Surprisingly, in Feature 27, the lateral canal, the aridity index varied randomly, suggesting periodic canal operation in contrast to the long-term flow indicated by the other two canals, suggesting that terminal canals, which are temporary, operated at periods of fresher water input.

Human impact in central Poland has been identified through the study of cladocerans and pollen from the Świerczyna mire in the Grabia River valley (Pawlowski et al. 2015) (Figure 2). The record spans 9,000 years, with Cladocera providing a valuable environmental signature not easily identified by other geological methods. In their study, Pawlowski et al. (2015) found six cladoceran assemblage zones based on the occurrence of species belonging to three families (Bosminidae, Daphnidae, and Chydoridae). The record is broken at times due to water-level fluctuations.

Water-level increase was associated with episodes of climate change that the authors also related to human activity in the area. The Grabia River moved a higher volume of water in

response to increasing rainfall but also as a result of higher rates of deforestation and soil erosion that affected the mire, resulting in corresponding changes in cladoceran frequency and diversity. Based on these organisms' chronostratigraphic records, four phases of wet climate conditions were recorded in Świerczyna mire (5800–550 BCE, 4500–4300 BCE, 4200–3800 BCE, and 400 CE). Anthropogenic influence was stronger in several phases too (1300 CE, 1500 CE, and 1650 CE), when human activity and wet climate left a clear imprint, particularly during the Middle Ages and in the last century.

Future prospects

Incorporating ostracod and cladoceran analysis with geoarchaeology will improve our ability to understand human–environment relations. Other research approaches such as investigations using shell chemistry may add more to our comprehension of environmental change in the future.

SEE ALSO: Geoarchaeology; Isotopes; Lake Deposits; Palynology

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Paleoethnobotany

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Paleoethnobotany refers to the scientific study of the interaction between humans and plants in the past; this includes the study of human impacts on the environment, how the environment directed human practice, and cultural uses of plants. It is simultaneously a subfield of archaeology and ethnobotany, which, in turn, are subfields of anthropology (in the American academic system) and botany or the plant sciences, respectively. In this sense, a paleoethnobotanist studies past human culture and plant life. In practice, this often consists of studying the remains of plants in archaeological sites, by a specialist, who draws upon methods and theoretical frameworks from both the biological and social sciences. In essence, paleoethnobotany is at the intersection of the interplay between living organisms and human culture. The term paleoethnobotany is also used synonymously with archaeobotany and advocates a multidisciplinary approach to studying human history. Specialists are required to mingle laboratory-produced data with historical texts, ethnographic analogies, cross-cultural comparisons, and a wide range of archaeobotanical data that are extracted from archaeological contexts, including ancient crafts made from plants, impressions of seeds and plant parts in ceramics or mudbrick, remains of plants in human paleofeces or in the stomach contents of preserved bodies, as well as artifacts or tools used to process or cultivate plants, such as grinding stones, farming tools, woodworking tools, digging sticks, loom weights or spindle whirles, and irrigation structures.

The most widely studied topic within the field relates to human paleodiet, and how humans cultivated or foraged for, harvested, and consumed plants in the past, as well as what kinds of plants they chose to eat. In

addition, some of the most widely publicized questions in the field surround the topic of plant domestication—including when certain plants were domesticated, how long this process took, where the domestication process took place, and why humans initiated the process. The origins-of-agriculture debate remains one of the most lively topics of inquiry in the archaeological sciences. Indeed, the plants that were morphologically domesticated as a response to human cultural practice express the closest coevolutionary relationship to humans, and, in studying them, scholars are looking at the deepest interrelationship that humans have with plants. There is also a wide array of research topics beyond plant cultivation; these include questions relating to how humans through time have impacted the environment that they live in, often dramatically reshaping plant communities, such as in agricultural fields or managed forests. All humans continually impact the plant communities around them, reshaping entire ecosystems and altering niches. In addition, plants are used for a range of cultural purposes beyond food and drink, including architectural construction material, textile and basket production, clothing, rope, fiber, and thread, weapons, hunting equipment, fishing nets and tackle, boat construction, ornamentation and art, dyes and paints, medicine, cosmetics, bedding, kitchen and household utensils and furnishings, fuel, ritual practices, and displays of status, identity, and aesthetics.

While the field is rapidly branching out into new methodological realms, including genetics (using ancient and modern DNA; see GENETICS: ANCIENT), isotope studies (see ISOTOPES), phytochemistry, proteomics, and other biomarkers, it has traditionally focused on the morphological identification of ancient plant remains. Many scholars in the field further subdivide paleoethnobotany into two primary branches based on methodological approaches: microbotanical and macrobotanical methods. The latter deals with all archaeobotanical remains that are large enough to see with the human eye, even if the identification of these remains requires magnification, whereas

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microbotanical approaches deal with plant remains that can only be seen with high-power magnification—phytoliths, pollen, and starch grains. Both methodological branches rely on morphological identification at a microscope; however, macrobotanical studies principally use dissecting microscopes with magnifications up to 50 $\times$, whereas microbotanical approaches generally use reflected or transmitted light microscopes at magnifications up to 1,000 $\times$. The field is largely quantitative, relying on the abundance and density of specific categories of plant remains in specific archaeological contexts. These counts and ratios go beyond simple observations of presence and absence and allow the specialist to determine cultural practices relating to plant use in specific areas of an archaeological site.

Plant tissue does not readily preserve; hence the archaeological recovery of these remains only occurs when specific depositional and taphonomic processes are met. Plants are consumed by fungi, including mold, animals, including insects, and microorganisms; only when the biological deterioration of these plants is prevented will they preserve in archaeological contexts. The majority of the macrobotanical remains recovered from archaeological sites have been burnt—carbonized or charred—either accidentally, such as by storage areas catching fire, or deliberately, when used as fuel or as discarded trash in a cooking hearth, resulting in their long-term preservation in anthropogenic sediments. Plant remains that have been carbonized will no longer deteriorate (rot) at the same rate as uncarbonized remains, as carbon is largely inert and not subject to biological or chemical attack, though such remains are vulnerable to physical and chemical weathering (see Miksicek 1987). Plant parts, such as seeds and fruit structures, can be preserved through other vectors, through which chemical, biological, and mechanical deterioration is halted or slowed, such as being incorporated into an anoxic environment (e.g., permanently waterlogged conditions or deep burial), or when desiccated, exposed to the corrosion products of metals, frozen, or through mineral replacement (e.g., calcium-phosphate replacement; see FORMATION PROCESSES).

The most widely studied category of macrobotanical remains includes seeds and fruit parts, such as nut shells; other archaeological remains of

plants include carbonized wood (see CHARCOAL AND WOOD ANALYSIS), pedicles, stems, textiles, and fibers (see TEXTILES), roots and underground storage organs, parenchyma tissue, and in some cases even leaves and floral structures. Carbonized macrobotanical remains are usually recovered from archaeological sites by means of a flotation/water separation system. There are several ways that excavators and specialists approach the systematic removal of botanical remains from anthropogenic sediments (for a discussion see Fritz 2005; Watson 1976); collectively, these methods are referred to as flotation. Flotation methods rely on buoyancy to mechanically separate carbonized plant remains from the soil matrix, dirt, rock, or other inorganic materials. Sieving is then used to remove all material below the target particle size.

In cases where macrobotanical remains did not preserve or as a complement to other lines of evidence, paleoethnobotanists can turn to microbotanical data, such as pollen. The study of pollen, or palynology (see PALYNOLOGY), has gone hand-in-hand with paleoclimatic studies for nearly a century. The most important use of pollen data for paleoethnobotanical purposes is to help elucidate changes in settlement patterns or possible anthropogenic impacts on vegetation cover. While pollen data are still most often used by scholars to reconstruct ancient vegetation communities, the data can also be used to understand aspects of human activities in the past. Pollen studies are sometimes conducted on sediments in archaeological sites, under the assumption that concentrations of pollen from economically significant plants may indicate processing areas or areas where flowers were concentrated, such as through a funerary offering.

Phytoliths (see PHYTOLITH ANALYSIS) are silica-based structures that form through the deposition of inorganic material inside or between plant cell walls. The particles serve the function of both providing structural support and reducing herbivory for the plant. Because the particles are inorganic, they are not subject to the same processes of biological deterioration as other plant remains and can preserve in situations where other organic material does not. However, not all plants produce the same abundance of phytoliths, nor are the same densities of these deposits produced in all parts of the plant. In

many cases, the morphology of the phytoliths is distinct to a specific clade of plants, allowing phytolith experts to identify categories of plant remains in archaeological sites, even if macrobotanical remains do not preserve. One of the most significant aspects of phytolith studies is the fact that these siliceous particles form in the leaves and stems of plants, leaving a signature of plant parts that are rarely preserved as charred remains.

Starch grains (see STARCH GRANULE ANALYSIS) are small granules of carbohydrates that form inside certain parts of some plants. They are commonly found in the fruits, roots, and seeds of many plants; in some cases, starch is stored in the leaves and stems of plants as well. While it is not exactly clear how carbon-based particles preserve in archaeological contexts, they have been recovered from dental calculus, ceramic sherds, organic materials, sediments, and stone tools. Starch grains often provide a direct indication of food processing, when found on grinding stones, or food consumption, when found in dental calculus or in cooking pots and on processing tools.

All of the methods mentioned above have positive and negative aspects and, therefore, they are best implemented in unison. Macrobotanical, rather than microbotanical, studies provide the most reliable line of evidence, and, in most cases, macrobotanical remains can be identified to a more specific cladistic level, often to species. However, phytoliths can be used in cases where macrobotanical remains do not preserve. Many studies have shown that these methods are complementary and produce data that highlight different aspects of the plants used by people in the past. For example, the glumes or chaff of grain crops contain phytoliths, and, therefore, finding high densities of chaff phytoliths in one area of a site may indicate that it was a crop-processing location. In addition, starch grains on archaeological tools and grinding stones have allowed scholars to determine what the tools were used for. Integrated or multivariant datasets are becoming increasingly more prevalent in the field, producing the most holistic picture possible. In addition, ethnoarchaeology has been tied closely to archaeobotanical interpretation for many decades. For example, studying what plant remains are found in recently abandoned pastoralist campsites in West Asia has helped scholars determine what vectors ancient plants

followed to ultimately end up in archaeobotanical assemblages (Spengler 2015). By studying these modern analogies, scholars can hypothesize whether specific seeds were introduced to a site as human food or if they followed another vector into the site, such as through dung or sod burning as fuel, through crop-processing to remove seeds from field weeds, incorporated into bedding or roofing material, or as seed rain—among a wide range of other possible vectors.

There are many historical overviews of the field, and the reader interested in understanding the development of paleoethnobotany should turn to sources such as Pearsall (2015) and Watson (1997). Pearsall (2015) suggests that the field was largely formalized into a system of inquiry with an article published by Volney H. Jones (1941) titled “The Nature and Scope of Ethnobotany”. In this article, Jones uses a broad definition for the field, noting that it centers on the study of the interrelationship of plants and humans; he also emphasized the interdisciplinary nature of the field, which is still one of its hallmarks today. While the systematic targeting and recovery of archaeobotanical remains may only date back to the 1940s, botanists have been recording and identifying plants in archaeological sites since the nineteenth century, with Kunth’s 1826 study of remains in Egyptian burials and Heer’s 1866 study of plant remains from waterlogged villages in the mountains of Switzerland. Furthermore, large-scale multidisciplinary expeditions, with scientific specialists including botanists on staff, have been undertaken for over a century, such as Pumpelly’s 1904 expedition to Anau in Turkmenistan. The term paleoethnobotany was first used in 1959 by Hans Helbaek; and Richard Ford’s definition from 1979 is still widely used today—“the analysis and interpretation of the direct interrelationship between humans and plants for whatever purpose as manifested in the archaeological record” (Ford 1979, 286). Over the past half century, the field has moved forward with new methods and technology in the laboratory, at the excavation site, and during data interpretation. As new technology and scientific methods are introduced, the questions that archaeobotanists are asking have become increasingly complex. Research questions addressed by specialists, by definition, deal with food and ecology, which

are inseparably intertwined with sociopolitical organization, ideology, and identity, exchange, kinship, adaptability, and ecosystem engineering. However, in the past few years, scholars have increasingly embraced a range of previously overlooked questions; one of the most intriguing of these is the topic of cuisine. These specialists are readily stepping beyond simple tallies of plant remains and instead discussing how the remains came together in a culinary tradition. In order to achieve this goal, they need to incorporate other archaeological artifacts, including tools and cooking pots, human osteological studies, and isotope analyses, as well as zooarchaeological data.

Plant domestication continues to be one of the most prominent areas of investigation (Langlie et al. 2014) (see DOMESTICATION), and with the incorporation of genetic approaches since mid-2000 scientists have largely rewritten what we know about the origins of our domesticated plants. For example, many specialists are looking beyond the idea of simple domestication models that rely on single centers of domestication and rapid domestication events, recognizing that many plants were domesticated multiple times and that this process may have taken several millennia. Increasing scientific investigation is also showing that the transition between hunting and gathering to farming is not a simple one and that many foragers also grew crops. Similarly, the introduction of archaeobotanical methods into parts of the world and time periods where archaeologists did not expect to find farming has been changing scholarship, notably in areas of Eurasia that were thought to be largely dominated by nomadic populations (e.g., Spengler 2015). In addition, many archaeobotanists are recognizing that questions concerning dissemination of these plants are as important as the identification of the original domestication; scholars are focusing more on plant spread and exchange. Other popular topics of investigation include human health and nutrition, plant pathologies associated with cultivation, the study of the spread of invasive species, the ramifications of deforestation, and the effects of global climate change in the long term. Furthermore, scientists are turning more towards multivariate statistics (see MULTIVARIATE ANALYSIS) and direct integration of plant and animal remains. Archaeologists acknowledge that plants are fundamental to human life and,

therefore, a comprehensive picture of human societies of the past cannot be drawn without the incorporation of paleoethnobotanical methods. As a result of the developments in the field of paleoethnobotany over the past half century, specialists are readily incorporated into excavations and the data they produce are held on par with other lines of archaeological investigation.

SEE ALSO: Paleoenvironmental Reconstruction; Paleoethnobotany and Ancient DNA Analysis; Paleoethnobotany and Stable Isotopes

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Paleoethnobotany and Ancient DNA Analysis

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Ancient DNA allows researchers to study changes in populations of humans, plants, and animals over archaeological time spans by analyzing genetic information from archaeological tissues (see [SEQUENCING DNA](#)). Combined with paleoethnobotany (see [PALEOETHNOBOTANY](#))—the study and interpretation of archaeological plants—ancient DNA can be used to investigate the domestication (see [DOMESTICATION](#)) of plants and the transition to agriculture, the human-mediated dispersal of plant species into new ecosystems and between societies, the evolution of plants as crops under human influences, food production systems, evolutionary ecology, and other topics at the interface of archaeology, botany, and ecology. In total, ancient plant DNA research provides real-time insight into evolution, demography, and population biology on the human landscape (see [GENETICS: ANCIENT](#) and [GENOMICS: ANCIENT](#)).

Ancient DNA fundamentals, applications, and challenges

DNA is the complex biomolecule that encodes an organism's fundamental organization, development, and physiology. The sequence of the four nucleotide bases that make up DNA (adenine, cytosine, guanine, and thymine: A, C, G, and T) not only underlies the structure and function of biological systems but also provides detailed insight into evolutionary relationships and demographic histories of organisms and species. Working with modern DNA sequence data can provide a wealth of information at a single time point of sampling, but integrating ancient DNA

is especially valuable in that it adds important time depth to analyses of population processes by allowing real-time insight into phenomena such as plant domestication.

By comparison with modern-only genetic approaches, ancient DNA analysis offers several benefits. First, ancient DNA harbors extinct variation no longer present in modern organisms. In domestic plants, for example, loss of diversity over time is an expected consequence of human cultivation, breeding, and management. By analyzing DNA from ancient plants alongside DNA from modern ones, these long-term trends in genetic diversity and structure can be directly examined across multiple time points instead of being inferred through the genomic vestiges of these population processes. Assessing the genomic characteristics of ancient crops falling on the continuum between wild types and modern cultivars can provide tremendous insight into the biological, ecological, and cultural processes associated with shifts in food production strategies.

Second, sampling DNA across the time frame of the archaeological record allows the unraveling of the myriad influences of various human activities on the genetic legacies of plants in human environments. In the long term, trade, breeding, and gene flow following plant domestication dramatically shape plant biology and genetics. More recently, economic development, population growth, rapid travel and communication, and similar effects of industrialization and globalization have massively altered the genetic landscape of global food production, and in many cases may overprint the genetic legacy of the plants that are historically important to humans. Currently, worldwide food calories are derived from a small number of cultivars in a handful of staple species—most importantly maize, rice, wheat, potatoes, sorghum, and cassava. The modern varieties of global importance often result from breeding programs that focus on productivity and predictable yield, whereas the evolution of these species alongside human cultivators is best understood by analyzing traditional landraces and archaeological materials. In short, modern

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plants important to humans are the result of diverse cultural and ecological histories, and ancient DNA analysis provides a direct mechanism to interrogate the strata of plants' unique legacies, in collaboration with paleoethnobotany.

Third, ancient DNA can provide a powerful means to resolve paleoethnobotanical uncertainty and test hypotheses related to ancient plant remains. Where morphological and anatomical characters are inconclusive, taxonomic identifications can be refined through genetic analysis of ancient tissues with suitable preservation. Further, if paleoethnobotanical analysis reveals morphological changes over time that are consistent with, for example, either rapid *in situ* evolution or replacement by a nonnative variety, these two scenarios can be probed through a population genetic hypothesis-testing framework. In total, ancient DNA can provide a data layer for complementing paleoethnobotanical analysis where information on genetic relationships and evolution can enrich the understanding of a region, time period, or plant taxon.

When compared with modern molecular biology, ancient DNA research involves two primary challenges: it is highly degraded; and it is highly prone to contamination by modern sources.

In living cells, enzymatic repair mechanisms are responsible for maintaining the structure and biochemical integrity of the DNA molecule. When replication error or the actions of DNA-degrading enzymes alter the sequence or nick the DNA backbone *in vivo*, for example, these repair mechanisms are evolved to restore DNA to working order and to ensure relatively uninterrupted cellular function. Thus DNA strands sampled from living or freshly deceased tissue can be recovered at hundreds of thousands of base pairs (bp) in length, and their sequences can be recovered with high fidelity. In ancient tissues, these repair mechanisms have long since ceased functioning in their protective role, and any remaining DNA is highly degraded. Over time, DNA is physically broken down into small fragments; an herbarium specimen or a desiccated seed typically has only a very small proportion of fragments greater than 100 bp, with the mode of recoverable fragments closer to 30 bp. This poses challenges both for recovering and, later, for analyzing ancient DNA. Moreover, postmortem chemical damage to individual

nucleotides accumulates over time in ancient tissue, and must be corrected computationally. Further, the majority of DNA fragments seem to be totally lost to damage or leaching, so that endogenous DNA concentration is much lower in ancient tissues than in their modern equivalents.

DNA degradation is a complex process with several environmental correlates, and the conditions for DNA survival are only understood at a rudimentary level. In general, however, samples from cool, dry, and thermally stable preservational contexts offer the best chances for successful ancient DNA recovery. Sample age is strongly linked with recoverable DNA content, and the oldest widely accepted DNA is from permafrost-preserved horse bone roughly half a million years old. For ancient plant samples, the best sites for DNA recovery tend to be dry caves, rock-shelters, and open sites in extremely arid climates such as coastal Peru and the southwestern United States. Waterlogged plant remains—from both saline and freshwater environments—have also produced DNA suitable for genomic analysis. Charred remains, by far the majority of paleoethnobotanical materials, are unfortunately very poor vessels for DNA preservation. Incomplete carbonization leaving some preserved organic matter has produced usable DNA in several experiments, but with charred plant remains a few successes are usually accompanied by many failed attempts. A wide variety of ancient materials have successfully yielded plant DNA under the right preservational circumstances, including starchy and oily seeds, maize cobs, grape pips, herbarium leaf and inflorescence tissue, fruit stones, peanut shells, squash and gourd rinds, wood, other vegetative structures, and even some sediments and residues. As yet, phytoliths and starch grains have not produced ancient nucleic acids, but DNA has been analyzed from pollen cores recovered from lake deposits.

Because of the degraded and low-copy nature of ancient DNA, contamination of tissues and experimental setups by high-quality modern DNA are a serious risk. Early studies reporting geologically ancient DNA recovery—including of dinosaur fossils and plant tissues preserved in amber—were ultimately attributed to contamination rather than extraordinary DNA preservation. However, these early issues with ancient DNA research led to the formalization of

criteria to detect, prevent, and mitigate the effects of contamination (Cooper and Poinar 2000). Standard protocols include working with ancient tissues in a lab that is physically separate from modern genetics experiments, wearing full-body personal protective equipment, disinfecting surfaces extensively with bleach and/or ultraviolet radiation, using “negative controls” in parallel with experimental tissue preparations to detect laboratory contamination, and taking other technical steps aimed at preventing contamination. Contamination can be especially problematic in human and archaic hominin research, where experiments can be compromised by researchers’ own DNA. However, ancient plant DNA contamination is also pernicious owing to the sheer environmental ubiquity of plants.

A timeline of ancient DNA and paleoethnobotany

In 1984 the first successful ancient DNA experiment was published in *Nature*; it reported a few hundred base pairs of sequence data from an extinct zebra relative called quagga, preserved in 140-year-old muscle tissue from a museum specimen (Higuchi et al. 1984; see ZOOARCHAEOLOGY AND ANCIENT DNA). This success laid essential groundwork by establishing that postmortem DNA could survive historic time spans; and it raised the realistic prospect of archaeologically and even geologically ancient DNA recovery. Following this proof of concept, the first methodological breakthrough for ancient DNA research was the Nobel Prize-winning development of the polymerase chain reaction (PCR), which allowed precise enzymatic amplification of target DNA fragments. PCR can be used to amplify extremely low quantities of target DNA, theoretically permitting a single copy of a rare target to be recovered for analysis. For this reason, PCR is especially useful for isolating target fragments from mixtures of degraded endogenous and environmental DNA typical in ancient tissues. The PCR method was developed in 1983 and first applied to ancient DNA in 1988 (Pääbo, Gifford, and Wilson 1988), with the successful amplification and direct sequencing of mitochondrial DNA fragments from ancient human tissue. In contrast with previous cloning and hybridization-based

methods for targeted DNA recovery, PCR is highly sensitive and can be deployed with a wide range of species and target DNA conditions. In total, PCR not only revolutionized molecular genetics as a whole, but dominated ancient DNA research for over two decades.

In recent years, PCR and amplicon sequencing have largely been supplanted by the second major breakthrough in the ancient DNA field: genomic technologies that permit sequencing millions of DNA fragments in parallel rather than narrowly targeted individual molecules. The first ancient genome—low-coverage whole-genome sequencing of a woolly mammoth using the Roche 454 platform—was completed in 2008, and the period since has seen exponential growth in the number of studies that apply genomic technologies to ancient DNA-based experiments. While PCR and targeted sequencing allow hypothesis-driven studies at the population level, PCR-based ancient datasets are fundamentally limited to the informative value of a few small fragments across dozens or hundreds of samples. On the other hand, genomic data facilitate a deep dive into the evolutionary, population genetic, and demographic context of ancient organisms through the recovery of very large datasets from individual tissue samples. For this reason, PCR and direct sequencing are rapidly giving way to genomic methodologies in ancient DNA research design across all fields, including plant research.

Since the first ancient DNA studies in the mid-1980s, plant specimens have been analyzed alongside human and animal tissues, and the field of plant archaeogenetics has developed and matured alongside ancient DNA research as a whole. In 1985, simple gel electrophoresis tests revealed the preservation of nucleic acids in a range of herbarium specimens and other desiccated plant tissues (Rogers and Bendich 1985). Although this approach was not conclusive as to whether the DNA detected was from plant tissues or from external sources such as microbes, this was the “quagga” moment for plant research; these experiments demonstrated fundamental tractability and set the stage for the exploration of the biological interface of plant–human interactions through archaeobotanical DNA. Throughout the 1990s, several studies sought to establish the limits of preservation of DNA in ancient plant tissues—including the plausibility

of retrieving DNA from charred seeds. Other early ancient plant DNA studies began probing for molecular signals in plant tissues that would address specific questions raised by archaeology. Early archaeological targets included aspects of the domestication and dispersal of maize (see MAIZE) and taxonomic identification in grain assemblages—a long-standing question for the spread of the Old World Neolithic crops.

Palmer, Smith, and Allaby (2012) review roughly a hundred ancient plant DNA publications from the PCR-dominated era of research—a nearly exhaustive treatment of the literature across tissue types and research orientations that illustrates the diversity of plant research from this period. They note that the most extensively archaeologically characterized gene of the PCR era is wheat (see WHEAT) glutenin (Glu). The genes in this family are generally compact, and therefore reasonably recoverable using very short fragments. More importantly, Glu is informative as to the movements and complex hybridization history of wheats in the Near East, which makes it a prime target for the application of genetic methods to archaeobotanical questions.

The genomic revolution reached ancient plant DNA research shortly after the 2008 woolly mammoth genome, when a method known as target capture was applied to maize and published as a methods comparison in 2011 (Ávila-Arcos et al. 2011). This technique, which uses synthetic RNA probes to isolate large panels of target DNA for efficient sequencing on a genomic platform, has since become a staple of the archaeogenomic toolkit. While this experiment first introduced genomic technology with ancient plants, an analysis of ancient cotton genomes the following year marks the beginning of hypothesis-driven genomics in archaeological plants (Palmer, Clapham et al. 2012).

The interceding years have seen a rapid growth of plant archaeogenomics using a suite of methods for diverse purposes and on a variety of tissue types. Genomic analysis in plants can present biological challenges not typical of human or animal studies. Broadly, plant genomes are of an order of magnitude more variable than animal genomes, and this adds layers of complexity for archaeological plant genomics. The human genome comprises roughly 3.2 billion base pairs (Gbp); this makes it typical of mammals,

which vary from ~2 Gbp in some bat species to ~8 Gbp in vizcacha rats, mammalian outliers. By comparison, domesticated members of the grass family alone range from 0.4 Gbp (in rice) to 15 Gbp (in bread wheat), a roughly tenfold greater span than the entire range of variation in mammal species. Moreover, animals are nearly all diploid—carrying two chromosome copies in each cell. Plant genomes also vary widely in this regard, whole genome duplication and hybridization leading to numerous instances of polyploidy throughout evolutionary history. Polyploidy occurs even in the compressed evolutionary trajectory of domestication—common bread wheat (*Triticum aestivum*) carries three chromosome copies from each parent, each acquired from a different species through hybridization during the process of domestication. This level of variation illustrates a tremendous capacity for genome restructuring and genomic plasticity that is not paralleled in most animals, which raises challenges to research design but also valuable targets for analyzing the complexities of plant systems on the human landscape.

At present, a small number of whole-genome studies from ancient plants have been published, and many more are in progress. The cost of data collection has decreased substantially in recent years, and methods for improved ancient DNA recovery and analysis have created new opportunities for ambitious research programs. Researchers are now deploying genomic methods to revisit archaeobotanical questions that were incompletely treated in the PCR era, and the range of testable hypotheses has expanded immeasurably with the breadth of data now being produced. Epigenomic profiles—chemical modification patterns in DNA, related to gene regulation and expression—have recently been shown to survive in archaeological material. The field of archaeoepigenomics, new and so far almost completely unexplored, offers potential for unprecedented insight into ancient plant–human interactions. Finally, modern plant genomics is itself a rapidly evolving discipline providing essential context and comparative data for archaeogenomic research, with a swiftly growing volume and diversity of available plant genomic resources.

SEE ALSO: Barley, Rye, and Oats;
Chromosomal DNA; DNA: Mitochondrial;

DNA: Next Generation Sequencing;
Environmental Archaeology; Grapes and
Viticulture; Potatoes; Rice; Use of Biological
Collections

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Paleoethnobotany and Stable Isotopes

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Stable isotope analysis of paleoethnobotanical remains provides a new technique to investigate crop cultivation, paleodiet, paleoclimate, and food exchange. The main elements investigated have been carbon and nitrogen, alongside hydrogen and oxygen for wood. The technique has principally been applied to cereal crops, mainly wheat and barley, but also maize, millets, pulses, rice, and sorghum. Application of the technique has been global in reach, and major studies have taken place in Europe and the Middle East on paleoethnobotanical remains from sites ranging from the Neolithic to the Roman period.

Stable isotope analysis of plant remains from archaeological sites was first undertaken in the 1980s, although plant remains have long been used for radiocarbon dating. During the 1990s, work concentrated on stable carbon isotopes, both studies of modern plants, and the investigation of water inputs to crops in the ancient Mediterranean. The 2000s saw a resurgence of interest in the investigation of plant remains, due to a combination of the increased understanding of the way isotopic ratios are affected by plant physiology and the application of the method to archaeological questions. Particular archaeological issues of long-standing concern include understanding crop cultivation conditions and the need to create plant baseline data for paleodiet studies. The large-scale application of isotopic approaches to archaeological plant remains over the last decade has been facilitated by the rigorous investigation of isotopic variation in modern field studies, taphonomy, sampling, and pre-treatment.

The application of plant isotopic ratios relies on knowledge of the ratios of specific isotopes in the soil or plant tissues. Photosynthesis discriminates against the heavier ^{13}C in preference for the

lighter ^{12}C isotope. The level of discrimination is affected by stomatal opening, and produces recordable separation in C_3 plants based on water status. Stable nitrogen isotope ratios of plant remains are linked to soil N of the growth medium, and can be used to infer potential addition of manure. The lighter ^{14}N isotope is preferentially lost from manure as volatile gaseous ammonia, resulting in ammonium enriched in ^{15}N , which is then taken up by plants.

Experimental studies have proven that environmental conditions have a measurable impact on stable isotopic ratios within plants. Field studies in the United Kingdom, Denmark, and Germany have shown that intensively manured cereal grains can have $\delta^{15}\text{N}$ values of around 8‰ higher than unmanured crops (Bogaard et al. 2013). However, ^{15}N enrichment in the soil can also be caused by wetland denitrification, salinity, aridity, microbial activity, and recent clearance. Experimental evidence from Morocco indicates that the aridity effect can be countered by factoring in annual rainfall and also through consideration of the $\delta^{15}\text{N}$ value of non-manured vegetation, extrapolated from wild herbivore $\delta^{15}\text{N}$. In relation to carbon, the $\Delta^{13}\text{C}$ notation is commonly used as it takes into account past fluctuations in atmospheric $\delta^{13}\text{C}$ values when extrapolating water status; $\delta^{13}\text{C}$ measurements from ice core records have been interpolated using the AIRCO2_LOESS system to calculate the $\delta^{13}\text{C}$ of air at different time periods allowing the conversion of $\delta^{13}\text{C}$ to $\Delta^{13}\text{C}$. Field studies of irrigated and un-irrigated crops in Syria and ethnobotanical studies of farms in Spain, Greece, and Jordan have established species-specific watering thresholds; for example, well-watered wheat has $\Delta^{13}\text{C}$ values of about 17‰ (Wallace et al. 2015). While there is consensus in the mechanisms behind isotopic fractionation, debate continues as to the interpretation of observed $\Delta^{13}\text{C}$ values.

The most recent applications of crop stable isotopic ratios have incorporated increasingly rigorous sampling and pre-treatment methodologies, which have further demonstrated that

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the isotopic ratios measured in grains are a reflection of variations in past growing conditions. A statistical understanding of the potential variation within cereal ears and within fields has been calculated experimentally. Approaches to sampling differ between those who analyze single cereal grains, in order to account for seed-level variability, and those who analyze bulk samples of ten grains or more, in order to understand field-level variability. Numerous experimental studies into the effect of charring on isotopic ratios have concluded that minor variations are produced in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$, an important factor to consider when comparing results with collagen-derived isotopic ratios (see ZOOARCHAEOLOGY AND STABLE ISOTOPES). Cereal grains and other crop remains are extracted from flotation samples taken from contexts or stratigraphic units excavated at an archaeological site. Contamination from carbonates, nitrates, and humic acid during burial can be removed through a range of pre-treatment techniques, usually including washing with HCl and NaOH. The use of Fourier transform infrared spectroscopy (FTIR) (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)) to identify contamination in samples can save on pre-treatment, and avoid further alterations to the isotopic ratios caused by pre-treatment.

The establishment of isotope values can inform upon the intensity of agricultural labor, community relations, and the resilience of agriculture in the face of socioeconomic changes. The method has been used to inform upon long-term socioeconomic changes within a region, as well as agricultural strategies within a single settlement. The analysis of 124 crop samples from 13 Neolithic sites (5900–2400 BCE) across Europe showed that the mean site $\delta^{15}\text{N}$ values of cereals were between 3 and 6‰, elevated above the estimated $\delta^{15}\text{N}$ value of un-manured wild forage, providing the first widespread evidence for manuring practices in Neolithic Europe (Bogaard et al. 2013). The $\delta^{15}\text{N}$ and $\delta^{13}\text{C}$ values of 320 crop samples from five sites in northern Mesopotamia (6500–2000 BCE) indicate a shift towards extensive or lower-input farming practices in the fourth and third millennium BCE (Styring et al. 2017). The investigation of $\Delta^{13}\text{C}$ values in 275 cereal and pulse samples from nine Neolithic and Bronze Age sites in the eastern Mediterranean

and western Asia demonstrated locally variable irrigation practices, with evidence from one Neolithic and four Bronze Age sites across the region for the preferential cultivation of wheat (see WHEAT) in wetter conditions than barley (Wallace et al. 2015).

Crop isotope analysis has also been used to investigate chronological and spatial intra-site variations in cultivation practices. At the Neolithic lakeshore settlement of Hornstaad-Hörnle IA in southwest Germany, the $\delta^{15}\text{N}$ values of 197 samples of naked wheat, einkorn, and barley (see BARLEY, RYE, AND OATS) demonstrated that different households were pursuing different cultivation practices. At nearby Sipplingen, analysis of 45 samples of barley, einkorn, emmer, naked wheat, and pea indicated that cereals were cultivated with medium to high levels of manuring from ca. 4000 – 2800 BCE. At both sites, wheat and barley were grown under different conditions (Styring et al. 2016).

Further to the assessment of site-based irrigation practices, stable carbon isotopic ratios of archaeological plant remains have been used to assess the impact of long-term climatic variation on human society. An analysis of $\Delta^{13}\text{C}$ values from 1,037 crop samples from 33 sites across the Near East (10,000–500 BCE) identified a correlation between drought stress, here defined as $\Delta^{13}\text{C}$ values below 16‰, and periods of climatic instability. The study highlighted the significance of regional variance in agricultural strategies (Riehl et al. 2014). Analysis of wood and charcoal (see CHARCOAL AND WOOD ANALYSIS) through isotope dendroclimatology has demonstrated that analysis of stable carbon, oxygen, and hydrogen isotopes can provide information concerning multiple climatic variables, including temperature and water status (McCarroll and Loader 2004).

Reconstructions of paleodiet (see DIET AND NITROGEN ISOTOPES) have often presumed that human and animal plant diets would be isotopically comparable. While the potential variation in both the carbon and nitrogen isotopic ratio of plant material has long been recognized, archaeological plant remains have previously been considered too rare and/or too contaminated to be useful in paleodietary studies. However, the inclusion of crop isotopic ratios in a linear-mixing model of the paleodiet at

Neolithic Vaihingen, Germany enabled more accurate estimates of past protein consumption to be made. Utilizing the $\delta^{15}\text{N}$ values of 16 cereal and pulse samples, alongside isotopic values of humans and herbivores, the study inferred that the percentage of animal protein in human diets was substantially lower (29–46%) than that calculated using the typical estimates of plant $\delta^{15}\text{N}$ of 3‰ (Fraser et al. 2013). Moreover, $\delta^{13}\text{C}$ values of plant remains provide baseline values of C_3 and C_4 plants, allowing a more nuanced understanding of the consumption patterns of both animals and humans.

$\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ are often used in biochemistry to characterize the source of food items, and there is potential to apply this technique to archaeological plant remains. Wide variations in $\delta^{13}\text{C}$ and $\delta^{15}\text{N}$ from Bronze Age Syria have been used to argue for multiple sources for stored cereals from a single site (Fiorentino et al. 2015). The question remains whether variation between isotopic values of crops could be reliably identified as intersite variation, rather than variation driven by climatic and crop husbandry practices within one settlement. More promising is the investigation of the radioactive isotope of strontium ($^{87}\text{Sr}/^{86}\text{Sr}$), a technique widely applied to investigate human and animal mobility (see MOBILITY AND STRONTIUM ISOTOPES). Experimental studies have indicated potential for applying such methods to archaeological plant remains, but problems of contamination need to be resolved (Fiorentino et al. 2015).

Isotopic analysis of archaeological plant remains holds great potential to address major questions in archaeology and paleoclimatology, if isotopic analysis continues to be integrated alongside other lines of paleoethnobotanical and archaeological evidence. The application of the methodology to periods other than prehistory and beyond Europe and the Middle East will shed new light on human–plant–environment interactions. The construction of site-specific plant baselines will provide valuable data for paleodietary studies, enabling more accurate estimates of past dietary protein composition, but further work is still needed to resolve the trophic offsets between plants, animals, and humans. Several key areas require further experimental study to ensure the reliability of plant isotopic values. First, there needs to be an increased understanding of

the effect of the nitrogen cycle on the $\delta^{15}\text{N}$ ratios of archaeological plant remains, in particular the effects of salinity, microbial activity, and species variation (Szpak 2014). Second, there are issues to be resolved concerning the contamination of uncharred plant remains. Third, quality control methods for isotope measurements, which are available for isotopic analysis of collagen, need to be established. Currently, studies use %C, %N, and C:N ratios (Szpak 2014). Finally, isotopic data need to be accurately reported and made publicly available in open data archives, and analyzed using reproducible methods

SEE ALSO: Diet and Carbon Isotopes;
Paleoethnobotany

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Palynology

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The term palynology was established in 1944 via correspondence within the *Pollen Analysis Circular* where a suitable new name for the publication was discussed, as the term “pollen analysis” was deemed inadequate because it excluded the study of spores. After a series of suggestions, it was proposed that the term palynology would be most suitable, derived from the Greek word *palunō* meaning “strew, sprinkle” and the English suffix *-logy* (“the study of”) (Edwards and Pardoe 2017). Palynomorphs are defined by their ability to resist most forms of decay, other than oxidation, and therefore can survive the acid digestion techniques used in their extraction from sediments. This resistance is due to an extremely tough, inert organic material composed of sporopollenin, dinosporin, chitin, or pseudochitin. Palynomorphs derive from both aquatic and terrestrial environments and are present in geological samples dating back to the Precambrian. Palynology does not include organisms with siliceous or calcareous exoskeletons, although these may be informally classed as palynomorphs when parts of these skeletons, such as the organic foraminifera (see FORAMINIFERA) test linings, remain after acid digestion. Although the term palynology is synonymous with pollen analysis, and is often used interchangeably, it is used by paleopalynologists to embrace a wider range of microfossils, most of which are useful in archaeological studies. The most common microfossils regarded as palynomorphs are as follows:

- Acritarchs: an artificial group, whose name means “of uncertain origin,” of any small (typically 20–150 μm), organic-walled microfossil which cannot be assigned to a particular group but is believed to be related to unicellular marine algae; useful for defining Paleozoic biostratigraphy.
- Chitinozoa: large (50–2,000 μm) flask-shaped marine microfossils of an unknown animal; useful for defining Mid-Paleozoic biostratigraphy.
- Scolecodonts: jaws of polychaete annelid worms (typically 100–4,000 μm) composed of chitin and silica; common in Paleozoic deposits, though have limited biostratigraphic use.
- Dinoflagellates: unicellular microplankton (typically 5–2,000 μm), commonly autotrophs but heterotrophic forms also occur, found in a range of water conditions but most common in marine environments; important biostratigraphic and paleoenvironmental tools for the Mesozoic and Cenozoic.
- Pollen and spores: Pollen grains are the reproductive propagules containing the male gametophyte of gymnosperms and angiosperms. Spores commonly included within this category represent the sporophyte stage of lower flowering plants (Cryptogams) such as ferns (Pteridophyta) and mosses (Bryophyta). The earliest spores are recorded in the Late Silurian, with gymnosperms appearing at the end of the Devonian and angiosperms appearing in the Cretaceous, and therefore are useful in defining the biostratigraphy across this entire geological timescale up until the modern day. They typically measure 201–250 μm , though some Late Paleozoic megaspores can be up to 3,000 μm . Because of the ease with which they are transported by wind, water, and animal hosts, they can be found in almost all environments and sedimentary deposits and are the most studied of all palynomorphs.
- Non-pollen palynomorphs (NPP): a “catch-all” grouping used to describe a range of microfossils visible in pollen preparations not covered by the above categories. A large number have been identified as remains of diaspores, cyanobacteria, green algae, rhizopods, fungi, invertebrates, and chormophytes. Although NPP were observed in early palynological studies, the systematic study

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of Quaternary NPP did not occur until the 1970s (see Miola 2012).

Samples for palynological studies can be obtained from sediments or organic material within stratified sequences (see CORING) or archaeological samples (see SAMPLING IN ENVIRONMENTAL STUDIES), or found directly adhering to archaeological material. Extraction techniques depend upon the type of palynomorph being studied, but will typically use acid digestion techniques, including hydrochloric acid (which removes carbonates) and hydrofluoric acid (which removes silicates; or equivalent heavy liquid separation technique), followed by oxidation, using either acetolysis or nitric acid, and then stained. Palynomorphs are identified using a compound microscope using transmitted light illumination, typically at $\times 100$, $\times 200$, and $\times 400$ magnification, or $\times 1,000$ oil immersion for detailed morphological identifications. Using taxonomic keys (e.g., Faegri, Kaland, and Krzywinski 1989), modern/fossil-type material, and high-resolution photographs, it is possible to use the distinct characteristics of each palynomorph to identify with a given type, family, genus, or even species. Palynomorphs, where modern equivalents exist, can be interpreted in two principal ways: first by comparing the fossil palynomorph assemblage to modern ones where the environmental conditions, such as vegetation composition or salinity, are known (modern analog method); and second, by using an indicator species, whose habitat is narrowly defined by ecological or climatic factors that have remained constant. Palynomorph preservation is strongly affected by various taphonomic (see TAPHONOMY) factors related to transport, deposition, diagenesis, and preservation potential, with poor preserving environments leading to either differential or total loss.

The earliest recorded descriptions of palynomorphs observed under a microscope were of pollen in the late seventeenth century, with dinoflagellates first described in 1753. During the nineteenth century, developments included the realization that pollen could be used for the systematic study of seed plants, and the first morphological descriptions and illustrations of palynomorphs were produced. Investigations of Paleozoic rocks revealed the presence of

fossil palynomorphs, notably dinoflagellates within Cretaceous chalk and pollen and spores within coal seams in England, Germany, and the USA. Beyond these early studies, there was limited development of the discipline until the pioneering work in Sweden by Lennart von Post and Gustaf Lagerheim looking at stratified pollen within Swedish peat deposits (see PEAT DEPOSITS). Von Post's 1916 address in Kristiania (now Oslo) is widely regarded as the birth of modern quantitative pollen analysis, leading to the introduction of many core aspects of palynology, including the pollen diagram, methodological advances in counting and dating, understanding the transport and preservation of pollen, and the phenomenon of regional parallelism in vegetation development and climatically mediated vegetational change (Edwards, Fyfe, and Jackson 2017). During the twentieth century, palynology had become fully embraced and evolved into a true interdisciplinary science, playing a key role in medical, geological, ecological, archaeological and forensic science, becoming an essential tool for the study of the past, the present, and the future of our planet.

The adoption of palynology into archaeology occurred early in the twentieth century when it was recognized that pollen could be used not only for paleoenvironmental reconstructions (see PALEOENVIRONMENTAL RECONSTRUCTION) but also to provide relative chronologies within a site or among a series of sites, based upon the concept of regional parallelisms and the construction of pollen zonation schemes aligned with the broad Late Glacial–Holocene climatic succession. It remained the main chronological tool until the invention and widespread adoption of radiocarbon dating from the 1940s onwards. Investigations of Pleistocene interglacial deposits revealed that pollen biostratigraphy could be used to correlate these deposits, withstanding testing by modern geochronological methods fairly well.

In 1937, Franz Firbas showed the possibilities of morphologically distinguishing between pollen from domesticated (see DOMESTICATION) and wild grasses. In 1941, Johannes Iversen was able to focus on specific archaeological questions using pollen, such as the start of the Neolithic period in Europe, based upon the decline in tree pollen and the appearance of

pollen of herbs and weeds typically associated with human occupation, including domesticated plants such as cereals. This introduced the concept that certain pollen types could provide “anthropogenic indicators,” along with demonstrating how humans had changed the equilibrium of the natural environment in the past. Rapid adoption of this approach occurred on all populated continents, and has been particularly effective in demonstrating the role that human impact has had in the formation of landscapes, including some long-presumed “pristine” regions. As the technique developed, notably through modern analog studies and modeling approaches to correct bias in pollen production and dispersal (see *VEGETATION MODELING USING POLLEN DATA*), quantified estimates of vegetation abundance strongly suggest that the influence of deforestation and agricultural activities on plant composition across northern Europe, from Neolithic times onwards, was substantially stronger than previously inferred.

Studies using pollen at the small scale also progressed throughout the twentieth century, notably those associated with archaeological sites, such as human coprolites and cadavers, buried soils, and pollen adhering to archaeological surfaces (e.g., ceramics or floors). These showed that pollen could be used to answer questions about human diet, use of plant resources, and the composition of on-site vegetation communities. It was also possible to highlight differences in the movement and deposition of pollen within urban environments compared to natural ecosystems (Greig 1982). Studies were undertaken into the detrimental impacts of humans upon their environment in the past, including soil erosion (see *EROSION*) and water pollution (see *WATER POLLUTION*), such as the introduction of non-indigenous dinoflagellate species into harbors and estuaries as a result of increased international trade.

While pollen has often been the main palynomorph used to address archaeological questions, there has been success in the use of NPP as both a complementary and stand-alone technique in environments where pollen and spores are not preserved. NPP can reveal additional details on a range of topics including human health from parasite ova and cysts (see *PARASITE OVA AND CYSTS*), livestock from

coprophilous fungi, ground destabilization and erosion from soil-inhabiting fungi, or burning from pyrophilous fungi.

Palynomorphs have also been particularly effective in identifying the provenance of rock materials, including stone and clay, found associated with archaeological sites. Using stratigraphic palynology, a branch of biostratigraphy, along with complementary techniques such as petrography, it is possible to use the palynomorph contents of materials to correlate them with stratigraphic sequences of known age and locations where these sequences are exposed (or have been quarried). Acritarchs, chitinozoas, and dinoflagellates have successfully linked artifacts constructed from Paleozoic stone or Mesozoic shale to their source locations, sometimes several hundred kilometers away. Similarly, when coal is encountered on sites as the fuel source, palynology can allow provenance to individual outcrops within coalfields. Palynology has also had some success in flint and chert sourcing studies, most notably by studying dinoflagellates contained within the raw material in order to resolve their geological age and provide a possible provenance (or at least eliminate some possible sources) to outcrops at a regional level (Harding, Trippier, and Steele 2004). Provenance studies can also be undertaken using palynology to ascertain the type of environment within which an artifact was created or stored prior to burial. Although palynomorphs are rarely preserved within materials that have been subject to high temperatures, such as fired ceramics, studies of poorly fired or half burnt potsherds have been shown to retain them, and can therefore be used to reconstruct the environmental setting where they were constructed.

The development of new techniques and applications within palynology, such as ancient DNA (see *PALEOETHNOBOTANY AND ANCIENT DNA ANALYSIS*) and advancing capacities for taxonomic precision, will allow the discipline to advance, as well as its inherent flexibility to play a major role in multidisciplinary studies and complement other techniques. Given the widespread adoption of palynology over the past century, generating vast amounts of data, the use of paleoinformatics offers an exciting opportunity to better understand past human impacts, including anthropogenic climate change.

SEE ALSO: Environmental Archaeology; Environment and Landscape; Paleoethnobotany

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Parasite Ova and Cysts

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Ova and cysts recovered from archaeological samples belong to a diverse group of intestinal parasites that can be divided into organisms visible by the naked eye, helminths, and microscopic taxa, protozoa. Cestoda and Trematoda (phylum Platyhelminthes, flatworms) are worth mentioning among the former, along with several species in the classes Secernentea and Enoplea, belonging to the phylum Nematoda (roundworms); protozoa are unicellular eukaryotic organisms, comprising amoeboid forms and other, often ciliate or flagellate species.

The interaction between humans and their parasites is a complex story that reaches back to the dawn of our species, when we shared the same microbiota with the ancestors of the other great apes (Moeller et al. 2016). The current ecology of intestinal parasites is particularly complex, as it results from an evolutionary history of a million years involving adaptation to several hosts in different environments. Contrary to popular opinion, the host/parasite relationship can also be a mutual one (McKenney et al. 2015). Parasites may have lived with humans much longer than previously thought (see HUMANITY AND ANIMALITY), and species infecting both people and other mammals may have developed before cohabitation with animals following domestication (see DOMESTICATION). This is indicated by phylogenetic studies (see DNA: MITOCHONDRIAL and GENOMICS: ANCIENT) supporting the presence of *Taenia saginata* (cattle tapeworm) in humans prior to cattle (see CATTLE) domestication, and is suggested by Mesolithic finds of possible eggs of *Trichuris trichiura* (although they might belong to *Trichuris suis*, the boar/pig-specific parasite).

Each species follows a specific life cycle, which cannot be completed without the appropriate host. Typically, a period of embryonation in a

suitable environment is followed by ingestion by one or more hosts, growth within their bodies, and discharge of the eggs with the stools. In the case of *T. trichiura* (human-specific whipworm), in order to survive, eggs need a permanence in a warm and humid environment for a period of about three weeks. However, after this period they become extremely resilient to environmental conditions. Hosts are infected through the accidental ingestion of contaminated soil particles. *Ascaris lumbricoides* (roundworm), the largest nematode in humans, follows a similar cycle but makes use of the bloodstream to carry the larvae to the lungs and eventually to the pharynx, where they are swallowed, prior to growth in the small intestine. An even more complex cycle is required for *Diphyllobothrium latum* (broad fish tapeworm) in order to infect humans. Embryos are ingested by freshwater crustaceans, which are eaten by small minnows, which are in turn predated by larger fish (see FISH). Humans contract the infection by eating raw or undercooked fish, and the tapeworm grows within the intestine, finally releasing eggs which are expelled with scats. If feces enter water, eggs become embryonated, leading to hatching of embryos, which are eaten by crustaceans, starting a new cycle. The *Dicrocoelium* genus (lancet liver fluke) involves two intermediate hosts (a land snail and an ant) to spread, and it is transmitted through the ingestion of an infected ant at the larval stage. Dicrocoeliasis often affects cattle, sheep, and goats (see SHEEP AND GOATS), and human infection is referred to as a case of pseudo-parasitosis, resulting from the consumption of infected animal liver. *Taenia* spp. (tapeworms) exploit humans as well as cattle and pigs (see PIGS) in order to complete their life cycle, and infection occurs through the ingestion of raw or undercooked meat.

The symptoms associated with helminth infection in humans are, in most cases, not very severe. Whipworms and roundworms may cause bloody diarrhea, vomiting, and iron-deficiency anemia (see ANEMIA). Diphyllobothriasis is associated with several symptoms, and because of the loss in vitamin B₁₂ the infected individual may develop

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anemia. The symptoms associated with dicrocoeliasis in mammals are weight loss, anemia, and cirrhosis.

Parasite eggs and cysts can be recovered from excavated layers, lake deposits (see LAKE DEPOSITS), coprolites (see COPROLITES), and even directly from exceptionally preserved bodies, such as mummies. The eggs are normally identified in pollen slides by means of high-power optical microscopy (see OPTICAL MICROSCOPY). Specific procedures for the extraction of eggs have been developed, involving sieving through 160 and 20 μm meshes. More rarely, parasite eggs are recognized in thin sections (see MICRO-MORPHOLOGY), although in this case a precise identification is arduous and volumetric or weighted samples should also be prepared to allow accurate observation of the eggs' shape and surface.

Eggshells of the genera *Trichuris* and *Ascaris* (nematodes) are by far the most commonly observed by paleoparasitologists, because of both the existence of human-specific species and the resilience of the thick-walled eggs. Eggs of *Trichuris* vary between ca. 45 and 80 μm according to the species, and are characterized by an elongated barrel shape with slightly convex polar plugs at both ends. The wall is smooth and formed by a superimposition of three layers (a lipid, a chitinous, and a vitelline layer), with the core of the plugs being of unknown composition. Due to overlapping size, it is difficult to separate *T. trichiura* from *T. suis* (infecting suids). The genus *Capillaria* produces similar eggs that can be easily mistaken for *Trichuris*, but the former displays a typical reticulate surface ornamentation and a slightly asymmetrical position of the polar plugs. Fertile eggs of *Ascaris* range from ca. 45 to ca. 70 μm in length, the most apparent feature being a knobbed coat (albuminoid uterine layer) creating an anastomosed pattern. To an untrained eye, this coat, in addition to the ovoid shape of the egg, may easily resemble fern spores of *Polypodium* spp. The outer coat of *Ascaris* eggs is often partially lost, so that the smooth surface of the underlying vitelline layer is exposed. *Diphyllobothrium latum* produces large elliptic eggs (ca. 60–75 μm in length) showing a wide aperture on one side; similar but smaller and more slender eggs (ca. 34–45 μm) with an aperture (after the loss

of the operculum) belong to the genus *Dicrocoelium*. Eggs of *Taenia* (ca. 30–40 μm) display instead a spherical shape, the wall being thick and striated on the surface. Other helminths, less frequently recorded in archaeological samples, comprise eggs of various taxa such as *Ancylostoma*, *Enterobius*, *Fasciola*, *Schistosoma*, and *Strongyloides*.

Protozoan cysts, despite being common human parasites, are almost never recorded in archaeological samples because of preservation issues and the requirement for more sophisticated techniques. Light microscopy is not effective, and the immunological technique enzyme-linked immunosorbent assay (ELISA) is required (Gonçalves et al. 2005). The infection is detected by identifying specific antibodies related to antigens. Both sediments and coprolites can be successfully analyzed using this method.

It is often difficult to identify parasites to a species level, and many of the remains recovered in archaeological deposits could also derive from feces of wild and domestic animals. However, their value is not limited to the information they can provide on diseases that would not leave any trace on skeletal remains (see OSTEOLOGY). The study of these microfossils allows inferences on early population movements, as well as supplying information about living conditions in ancient settlements, providing data on dietary practices, use of the space, and social status.

One line of research involves the investigation of the origin and spread of human parasitic infections, using paleoparasitological evidence to shed light on large-scale movements of early human groups and the occupation of previously uninhabited continents. The arrival of hunter-gatherers in North America only through Beringia has been questioned, as eggs of *Trichuris* and *Ancylostoma*, requiring warm and moist soils, would not have survived in soil in the arid and cold permafrost. It is then difficult to explain the presence of these human-specific species in the stools of ancient populations in the Americas, and alternative colonization routes have been proposed (Araújo et al. 2008).

On archaeological sites, the informative potential of parasite eggs is manifold. They are useful indicators of dietary habits (e.g., consumption

of raw fish: Yeh et al. 2014) and poor hygiene during food preparation (e.g., soil contamination). Changes in subsistence strategies may be inferred by increases in certain parasitic species, such as in the case of fish tapeworm indicating fishing activities in Late Inca coprolites (Santoro, Vinton, and Reinhard 2003). In settlements, knowledge of the use and organization of space can be gained, as areas such as latrines and stables can be particularly rich in parasite remains (see MICROARCHAEOLOGY) (Langgut et al. 2016). Differences in social status, reflecting habits of different parts of the population, can also be detected. For example, in late medieval France, the abundance of *Taenia* eggs in cesspits adjacent to high-status mansions, relative to their absence in poor contexts, showed the consumption of raw meat as a specific practice within aristocratic families (Bouchet 1995). In graveyards, inhumations can be specifically sampled for paleoparasitological analysis in key areas, such as around the pelvis.

In paleoecological studies (see PALEOENVIRONMENTAL RECONSTRUCTION), parasite eggs of herbivores are useful indicators of local grazing pressure, as, unlike pollen and spores (see PALYNOLOGY), they are not transported over long distances by atmospheric agents, but deposited within dung pats and droppings.

In recent years, molecular paleoparasitology has become increasingly important, as it allows detection of infection even when eggs are not visible in routine microscopic analysis. Analysis of ancient DNA using the polymerase chain reaction method coupled with next generation sequencing (see DNA: NEXT GENERATION SEQUENCING) enables extremely accurate species-level identification in sediments and coprolites, opening new frontiers of paleoparasitological investigation (Côté et al. 2016).

SEE ALSO: Infectious Disease; Paleopathology; Parasitology

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Peat Deposits

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Peat deposits occur when decomposing organic matter accumulates due to a reduction in microbial decay, usually through the process of waterlogging, which creates anerobic conditions in the organic layers below. Large landmasses in the northern hemisphere, such as those of North America, Europe, Russia, and Asia, coupled with climatic conditions that are mild/cold and humid, means that the northern hemisphere contains approximately 88–95 percent of the world's peat deposits. In spite of this dominance, significant peat deposits do exist in the southern hemisphere, particularly in tropical regions, in the form of mangroves and peat swamps.

Types of peat

Areas where peat deposits form in the northern hemisphere are given different names depending upon their characteristics:

- Bogs: are only fed by direct rainfall (ombrotrophic).
 - Raised bogs are isolated areas of peat; they usually form in the lowlands over depressions such as kettle holes, on floodplains, or in estuaries.
 - Blanket bogs form extensive areas in uplands.
- Fens: form where groundwater causes waterlogging, and they are characteristic of lowland areas.
- Mires: are active (or potentially active) systems where peat is currently being formed.
 - Blanket mires are where bogs and fen systems interconnect over large areas; these occur in Scandinavia.

The importance of peat deposits

Most peat deposits have accumulated over the Holocene, during the relatively mild and increasingly humid period since the last glaciation. The lengthy formation period undergone by deep peat deposits means that they have built-up a long-term record of proxy indicators for Holocene environmental, climatic, and anthropogenic change. Peat can preserve rare and significant organic archaeological remains, such as bog bodies, trackways, cloth, wooden artifacts, and occasionally food remains. While we can research both the natural development and human usage of peatlands in the past, the two are not separate, and arguably they are becoming increasingly linked, especially with the growing pressures facing peatlands.

The contemporary and future fate of peatlands has significance to archaeology and paleoecology, but also to the wider world. Over the centuries, as the peat has formed from rotting vegetation, so the carbon that was contained in the vegetation becomes locked away, making the peat into a large natural carbon storage unit. Approximately one-third of the world's soil carbon is contained in peat deposits. As peat deposits are excavated, drained, or burnt, this carbon is emitted into the atmosphere as the greenhouse gas (GHG) carbon dioxide, along with methane and nitrous oxide. With such a strong focus on reducing global emissions since the Paris Agreement in 2015, understanding, managing, and restoring peatlands is becoming an increasing global priority, not just for archaeology and wildlife, but also for the health of the planet.

How peatlands have been used in the past

While peat deposits are valued today as carbon sinks, and archives of valuable information about past environments, they were valued in ancient times for very different reasons. In upland and/or moorland contexts, peat often provided the only

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source of fuel for cooking and heating. Peat was cut into blocks, and then dried and stacked ready for use. Evidence of burnt peat has been found at a range of archaeological sites, including Neolithic and Bronze Age sites in Orkney, medieval sites in Greenland, and early medieval sites in Ireland.

The peatlands, or the wetlands that were present before the peat started to form, have been significant sites for votive deposition since late prehistoric times (approx. 800 BCE). These depositions have included human bodies, in the form of bog bodies, weapons, and food. The reasons put forward for deposition into peaty areas are many and varied, from them being boundary areas (between wet and dry, air and water, life and death), areas associated with bounty and fertility, or perceived as desolate and wild, to even just areas where accidental deaths and losses occurred and the burial environment led to their preservation. While we cannot fully arrive at an “answer” for how these boggy areas were perceived (see PERCEPTION AND EXPERIENCE), we can, as Giles (2009) points out, construct an interpretation (see INTERPRETATION) about peatlands and their usage by going through an “interpretive process of excavation, analysis and display.” The following section describes some of the methodologies needed for excavating and analyzing peat deposits; these are primarily rooted in an empirical (see EMPIRICISM) framework that is often more closely aligned with paleoecology than with archaeology. However, this does not mean that the study of peat deposits should always split along disciplinary lines; more that there is an increasing need to recognize that they will be studied, perceived, and understood by people with different epistemologies. This is especially the case as the threatened status of peatlands means that people from varying backgrounds (conservation, ecology, archaeology, paleoecology, history, art, literature, and general local interest) are increasingly working together.

How peat deposits are studied

Sampling

The sampling of peat deposits occurs in two ways, either through coring or from an exposed section

(see SAMPLING IN ENVIRONMENTAL STUDIES). Coring allows the extraction of a thin core (usually ca. 5–15 cm diameter) from above the deposit in question. The effect is much the same as coring an apple. The advantages of coring are that it does not rely on the presence of an excavated site; multiple cores can be extracted relatively quickly; and a greater depth can be reached compared to excavation alone, including going beyond the water table. Sampling from a section usually from within an excavated archaeological trench or from a section exposed as a result of erosion, such as a stream-cut or cliff, is carried out using bespoke monolith tins or guttering. The benefits of taking monoliths from sections are that the analyst has the advantage of seeing the stratigraphic context and can choose the best placement of the monolith tins based on factors such as proximity to other archaeological material and areas of potential disturbance. Second, larger subsamples can be obtained for analyses.

Characterizing the deposit

Peats are firstly characterized and described, usually at the point of sampling, in relation to their degree of humification (the breakdown of the organic material). The main system of field description employed in the northern hemisphere is the Troels-Smith (1955) scheme; initially developed in the 1950s, this system describes the composition, degree of humification, and the physical properties of the deposit (Rabby 2013). These initial descriptions are often tested when the samples arrive in the laboratory (see ‘Geochemistry’ below).

Macroremains

Common macroremains that can be found in peat deposits include:

- wood
- macroscopic plant remains (see PALEOETHNOBOTANY)
- insects (see ARCHAEOENTOMOLOGY)
- molluscs (see LAND AND FRESHWATER MOLLUSCS)
- human remains, including soft tissue such as skin, as well as bone, hair, and finger nails

- vertebrate remains (see ZOOARCHAEOLOGY)
- other archaeological remains such as flint, pottery, and metal work, fibers (see FIBERS), and residues (see ORGANIC RESIDUE ANALYSIS).

Some of archaeology's most enigmatic sites and finds have been from peat deposits, primarily due to their ability to preserve organic remains that are often lost on dryland sites. These finds have included those from 2000 BCE–120 CE (Bronze Age–Roman period) bog bodies from all over northern Europe, such as Tollund Man (Denmark), Kayhausen Boy (Germany), Cashel Man (Ireland), Weerdinge Men (The Netherlands), and Lindow Man (UK)—all of which had substantial or fatal wounds.

On a landscape scale, the Somerset Levels, UK, have seen prolonged and extensive work on both the archaeological and paleoecological micro- and macroremains contained within the peat deposits. These have included the excavation and analyses of trackways and lake villages. More recently, the condition and hydrology of the peat itself has been assessed for the future management of these sites (Brunning 2013).

Microremains

The most frequently analyzed microremains—and probably the most familiar to archaeologists—are pollen grains (see PALYNOLOGY), although a range of analyses on other microparticles and -organisms can also be highly informative about the past environment and its usage. These include:

- Nonpollen palynomorphs (NPPs) such as fungal spores and parasite ova (see PARASITE OVA AND CYSTS). Frequently found on pollen slides, these microfossils can provide other proxy evidence alongside pollen, which is often related to the local environment, and particularly to hydrological conditions in peatland contexts.
- Testate amoebae (see TESTATE AMOEBEA ANALYSIS): These single-celled organisms survive well in peat deposits and can be used as indicators of hydrological change in peat bogs over time. They respond to changes in

moisture on the surface of the peat, allowing a transfer function (an equation) to be applied, which allows past changes in the water table to be inferred.

- Diatoms (see DIATOMS) that are present in all aquatic environments can be used to reconstruct hydrological changes in the peat.
- Charcoal: Microcharcoal is often encountered on pollen slides, and while the cause of the fire (human or natural) often remains obscure, its presence can inform us about past landscape change within the local area of the site, and up to ca. 96 km (60 miles) away.
- Spheroidal carbonaceous particles (SPCs): These small particles, ca. 50 μm in diameter, are the product of the incomplete burning of fossil fuels at high temperatures that are required for industry (see AIR POLLUTION). They provide an indication of past industrial activity and, as such, can be used as chronological markers within a peat sequence for the historic period (see below).

Geochemical analyses

The chemical properties of the peat deposit itself are important for understanding the environmental and climatic conditions under which the peat formed, activities occurring around the sites, taphonomic processes that may have affected (and continue to affect) macro- and microfossils within the peat, and potentially how the peat may respond in the future to changing conditions (see SOIL CHEMISTRY IN ARCHAEOLOGY). Peat is primarily composed of organic material, but it also consists of a smaller inorganic fraction. This inorganic fraction provides information about conditions or activities that usually occurred off-site, such as erosion (natural or human-induced), industry, fire, and wind-blown dust movement. The following methods can be used to study the geochemistry of peat deposits:

- Organic geochemistry: The amount, or degree, of humification of the peat is an indicator of how much vegetal decomposition has occurred. Very simply, in dry or warm periods, peat becomes more humified (dark and finer) as decomposition occurs; however,

this should be tested against other proxies for moisture as well. Given that peat is composed of decaying vegetation, all peat is humified to some extent, but this will vary depending on the type of peat, the climatic and local conditions, time, and depth. The degree of humification was traditionally established by visual inspection (see “Characterizing the deposit”) but is now increasingly undertaken by pyrolysis gas chromatography and Fourier transform infrared (FTIR) spectroscopy (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)). Bulk analysis of the carbon–nitrogen ratio can also indicate the degree of decomposition.

- Inorganic geochemistry: Elemental and isotopic analyses are increasingly undertaken on peat deposits. Potentially the most useful analyses undertaken from an archaeological perspective are those relating to heavy metal pollution, for instance lead (Pb) pollution from mining activities. Analysis of the inorganic chemical composition of peat is increasingly undertaken through X-ray fluorescence (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)). Elemental analysis has usually been carried out by removing organic matter and water content from samples before analysis, but, more recently, experimentation with scanning complete cores has been carried out.

A case study that combines microfossil and geochemical analyses from a peat deposit in central-western Spain can be found in the work of Silva-Sánchez et al. (2016). Here, pollen, NPP, and charcoal analyses were combined with organic and inorganic geochemical analyses for a sequence dating to the Little Ice Age (sixteenth to nineteenth centuries) in order to examine the effects of climate change (temperature and moisture) on carbon accumulation, and the effect of land use change on erosion and mineral influx.

Chronologies

Due to the more-or-less continuous accumulation of organic matter in most peat deposits, they are ideal for the construction of age-depth models (models that allow us to interpolate

between known ages). The recent increase in the usage of programs such as OxCal and Bacon (for references see Piotrowska, Blaauw, and Mauquoy 2011) for the creation of Bayesian age-depth models has allowed a move away from the previously favored (and highly inaccurate) method of linear interpolation, which involved purely drawing a line between dots. Instead, Bayesian age-depth models are created that take into account the errors associated with each individual measurement, in conjunction with all relevant prior knowledge about the site/sequence in question (e.g., stratigraphic changes, distance between the radiocarbon determination). Advantages, they also permit statistical estimations to be made for undated points on the age-depth curve between measurements; and they can provide a more precise estimate for the original calibrated date. Bayesian age-depth models can be constructed with dates obtained from various sources; those that can be employed on peat deposits include:

- Radiocarbon dating: When choosing samples from a peat sequence, it is best that short-lived plants are chosen, particularly those growing on the site, such as *Sphagnum*. For highly humified peat, it is not always possible to select an in-situ plant macrofossil, in which case either bulk samples or fractions of the samples can be dated. Wherever possible it is best to obtain dates on both the humic (acids from the decomposing vegetal matter) and humin (the organic detritus) fractions of the peat; ideally there will be consistency between these measurements, but where they differ, the humin fraction is generally regarded to be the best approximation, due to the fact it is less mobile through the profile than the humic acids (Piotrowska et al. 2011). However, this decision can only be made on a site-by-site basis.
- Spheroidal carbonaceous particles (SPCs): Within the UK and Ireland, a database (CARBYDAT) of SPCs has been produced to allow the regional dating of peat and lake sediments from the 1800s (Rose and Appleby 2005).
- Tephrochronology (see TEPHRA AND VOLCANIC ASH ANALYSIS).
- Dendrochronology: This technique is especially useful where archaeological material,

such as trackways, structures, and wooden artifacts, survive within the peat. The first pre-historic chronologies based on oak tree rings in the UK were outlined in the mid-1980s and used to provide a date of 3807/6 cal BCE for the Sweet Track, a Neolithic trackway running ca. 2,000 m (6,600 ft) across the Somerset Levels, UK (Hillam et al. 1990) that was subsequently preserved in the peat that consumed it.

- ²¹⁰Pb dating: Naturally radioactive lead-210 occurs in the atmosphere and eventually settles into soils and sediments. This radiometric dating technique is only suitable for dating deposits that have accumulated over the last ca. 100 years due to its relatively short half-life (22.3 years).

Threats to peat deposits and the archaeology contained within them

Today, the largest threats to peat deposits in the northern hemisphere are their continued commercial extraction for (1) use as a fuel, especially for heating and power generation in Finland, Ireland, and Sweden; and (2) use in horticulture and agriculture, for example for compost or soil improvement. Another significant problem facing peat deposits, especially in lowland areas (and in the southern hemisphere), is deforestation and drainage of peatlands for cultivation; this effectively lowers the water table, which not only allows the release of stored carbon, but also encourages the degradation of any organic material contained within the peat. Experiments on the effects of a changing and fluctuating water table in peat deposits on archaeological material at the Mesolithic site of Star Carr, North Yorkshire, UK, have shown that water-management practices in peatlands can severely affect the preservation of organic remains; for example, both bone and wood were found to have deteriorated irreparably within a shockingly short period of time: just one year (High et al. 2016). This in turn has implications for the in-situ preservation of any archaeological sites and artifacts contained within peat deposits and for the preservation of micro- and macro-environmental remains.

SEE ALSO: Lake Deposits; Paleoenvironmental Reconstruction

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Phytolith Analysis

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The term phytolith refers to biomineral deposits that form within and between the cells of plants. Most often phytolith refers to opaline silica ($\text{SiO}_2 \cdot n\text{H}_2\text{O}$) deposits which form a three-dimensional “cast” of the cell morphology, but is sometimes also used for other plant mineral deposits such as calcium oxalate ($\text{CaC}_2\text{O}_4 \cdot \text{H}_2\text{O}$). Calcium oxalate deposits form crystals within different parts of the plant rather than forming cell casts. Forms include granular or rosette-shaped crystals called druses, needle-shaped crystals called raphides, various prismatic shapes, rectangular styloids, and block-shaped aggregates called “crystal sand.” Calcium oxalate crystals can be a major component of plant ash; however, they are removed through standard phytolith processing methods and are not often studied in archaeological samples. There are also problems in distinguishing these from naturally occurring calcite crystals, which have similar morphologies and optical characteristics.

Silica is present in the soil from weathering of silicate minerals such as clay and feldspar, and is absorbed by plants in solution in the form of silicic acid. The silica is transported throughout the plant and deposited in areas with high evapotranspiration, most commonly in the epidermal cells of leaves, stems, and bracts. Short cells (such as rondels and cork cells) within the epidermis are the first to become silicified and in some cases may be the only cells that silicify. Other types of cells such as hair cells and stomata guard cells can also become silicified. Certain types of plants accumulate silica in greater quantities than others. Monocotyledonous plants, particularly Poaceae (grasses, including cereals) and Cyperaceae (sedges), and Equisetaceae (horsetails) have high rates of silica deposition, which can be up to 4 percent by weight. Intermediate deposition between 2 and 4 percent is seen, for

example, in Cucurbitales (squashes) and Urticales (nettles).

Factors influencing silica deposition are complex, and include soil pH, availability of water and nutrients during plant growth, and climatic conditions. The mechanisms of deposition are largely determined genetically and some plants actively accumulate silica regardless of external factors. This is thought to be related to pest resistance. Environmental factors, however, have a significant influence, with high availability of silica and water flow favoring phytolith formation. For this reason, phytoliths are produced in much greater quantities in environments with high evapotranspiration rates. In these environments whole sections of plant tissue can become silicified, forming very large phytoliths where hundreds of individual cells are conjoined. These are often referred to as “silica skeletons.” In more temperate environments the degree of silica deposition is much lower, leading to lower numbers of phytoliths which are less well formed, making research in such regions more challenging. In these environments only the individual cells are recovered.

The history of phytolith analysis can be traced as far back as the 1800s, when they were first reported by the German scholar Struve, who wrote a dissertation on the subject in 1835, and “phytolitharia” were identified in dust collected by Darwin on the *Beagle* (Darwin 1846). In the later nineteenth century and early twentieth century, phytoliths were studied mainly by botanists, with the earliest archaeological studies conducted in the 1950s and 1960s. A turning point came with the publications of Rovner (1971) and Piperno (1988) that helped establish phytolith analysis as an important tool within archaeology and paleoecology. The technique is now well established, though not routinely applied.

It is a particularly useful technique as phytoliths survive when other types of plant remains do not, as they do not have to be burnt or waterlogged to preserve in the archaeological record. Phytoliths survive in most environments, being subject to erosion in conditions of extreme high

pH, and even in these circumstances they may survive in a weathered form. Phytoliths have been utilized for a wide range of research areas, including studies of diet, agriculture, fuel use, examination of architectural and craft activities, and detection of activity areas. Compared to other microfossil analyses such as palynology (see PALYNOLOGY), our understanding of the formation processes (see FORMATION PROCESSES) and taphonomy (see TAPHONOMY) of phytolith assemblages is relatively poor. Unlike pollen, phytoliths are usually assumed to occur “in situ,” with limited transportation by wind and water, and thus are assumed to give a highly localized signal of plant presence. However, experimental work has recently questioned this assumption, indicating that phytoliths can be moved through other mechanisms and do not necessarily represent in-situ deposits. Sampling strategies need to take into account these issues, and will depend to an extent on the questions being asked.

Phytoliths can be extracted from bulk sediments, specific microarchaeological layers, and “sealed” contexts such as within dental calculus and burnt food residues (see FOOD RESIDUE ANALYSIS) on pottery. Understanding the precise depositional context is important for interpreting phytolith assemblages. Combined phytolith and microstratigraphic analyses have demonstrated that similar phytolith assemblages can occur in deposits that come from a diverse range of activities (Shillito 2011). Samples collected from artifacts are less problematic as it is easier to associate the microfossils with the specific deposit/activity. Other approaches include horizontal or systematic sampling across a defined surface at regular intervals, in order to map densities and identify potential activity areas. As with other techniques, such as geochemistry, that aim to map concentration and variation across a surface, this approach can be problematic as it is not always easy to identify the origin of deposits, and several layers/activities can be mixed. Sampling vertically through soils is also an option, to examine change in the phytolith assemblage over time, though movement of phytoliths throughout the soil makes this problematic.

Studies combining phytolith analysis with thin section micromorphology (see MICROMORPHOLOGY) have become increasingly common

to try to identify and account for these formation processes (Albert et al. 2008; Vrydaghs, Ball, and Devos 2016; Sulas and Madella 2012). This approach can also identify whether movement is occurring in sediments, and by which mechanisms, for example, bioturbation or percolation. By microsampling thin section blocks, a direct link can be made between the phytolith assemblage and the precise depositional context, and can help identify whether there is a single deposit or cumulative palimpsest.

A major area of phytolith research is the identification of domesticates, crop processing, and agricultural practices. Research on modern plants has shown statistically significant differences in the average shape and size of phytoliths in domestic compared to wild varieties of plants, including maize, rice, and wheat. Caution needs to be applied in archaeological studies, where small numbers of phytoliths may not provide a sample set that is large enough to unequivocally distinguish between morphologically wild or domestic forms (Shillito 2013). A further strength of phytoliths compared to other botanical remains is the ability to identify different parts of the plant, for example leaves and stems versus chaff and husks, which in turn enables agricultural activities such as crop processing to be inferred. It is also possible to identify whether plants have been irrigated (or, at least, the extent of water availability), on the basis of tissue size and the ratio of short cells to long cells.

Phytoliths from ash deposits can be used to identify both wood and nonwood components of fuel. Ash that results from the burning of wood is calcite rich with amorphous silica phytoliths and oxalate pseudomorphs, whereas the burning of reeds and grasses produces silica-rich ash with morphologically distinct phytoliths. The presence of phytoliths from reeds and sedges can also provide information on the exploitation of wetland resources for activities including matting and roofing.

The ease with which specific genera or species can be identified varies considerably. As they are exact replicas of plant cells, an understanding of plant cell morphology can help the process. The large articulated tissues that are seen in some parts of the world are relatively easy to identify taxonomically through comparison with reference collections. In many cases such tissues

are not formed or are not preserved, and we have only individual or small groups of cells. In this case only a general grouping can be made, and a typological approach can be used to try to link a phytolith to a particular plant part or taxa. The International Code for Phytolith Nomenclature (ICPN) was proposed (Madella, Alexandre, and Ball 2005) as a means of standardizing typological descriptions; however, there is still considerable variability in the application of the ICPN, which makes comparative studies difficult.

A further problem in phytolith analysis is the huge degree of variability in phytolith morphology, and the fact that similar morphologies can be found in different taxa, which may or may not be related. It is important therefore to be realistic about the level of identification that can be achieved in different circumstances, and the interpretations we can make. It is not always necessary to be able to assign a specific genera or species; for example, the morphology of short cells can be used to identify whether an assemblage is dominated by C3 or C4 plants, which in turn can help with paleoenvironmental reconstructions.

Geographically, phytolith analysis has seen greatest applications in the Americas, South West Asia, and East Asia, with an increasing number of studies being conducted in temperate Europe as researchers work to address the limitations of the technique in these environments. Current emphasis in archaeological contexts has been on understanding taphonomic processes and depositional pathways, where ethnoarchaeological and experimental studies are providing important insights. The integration of phytoliths with other data as part of multiproxy approaches, already standard within paleoenvironmental research, is also becoming increasingly common in archaeology.

SEE ALSO: Ethnoarchaeology; Paleoethnobotany

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FURTHER READINGS

Pigs

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The pig (*Sus domesticus*) is one of the most important domestic animals, contributing substantially to human diets, cultures, lifestyles, and beliefs. Along with cattle (see CATTLE), sheep, and goats (see SHEEP AND GOATS), it was one of the earliest animals to be domesticated. Only dogs were definitely domesticated earlier. As the domestication of the pig was part of a process that led to the “farming revolution” and the advent of the Neolithic, it is no exaggeration to suggest that it transformed human life on earth as no other innovation.

The wild ancestor of the domestic pig is the wild boar (*Sus scrofa*), whose original distribution includes most of Europe, Asia, and North Africa. The wild boar is a typical woodland species, though its habitat can be diverse and, in its range, the species is only absent from the driest and coldest environments. The wild boar was an important game species for many Paleolithic and Mesolithic populations, as well as for later prehistoric and historic societies. In classical and medieval times the hunting of wild boar was regarded as especially dangerous and therefore only suited to the bravest hunters. Classical mythology contains many references to wild boar. One of Heracles’ labors consisted of the chasing of a giant wild boar; it is through a scar ensuing from a wild boar hunt that Odysseus is recognized on his return to Ithaca; and Mycenaean noble warriors wore wild boar tusk helmets, as described in Homer and Mycenaean iconography, and demonstrated by archaeological evidence.

Due to the wide geographic distribution of its wild ancestor, potentially the pig could have been domesticated in many different areas. There is, however, some consensus that the initial domestication occurred in the Near East, with Turkish sites such as Cayönü and Hallan Çemi providing some of the earliest evidence (ca. tenth to seventh millennium BCE) (Rosenberg et al. 1998; Ervynck

et al. 2002). Genetic research, however, has led to the suggestion that the domestic pig is the product of multiple domestication events, occurring in different parts of the world. Independent domestication in the Far East is nowadays regarded as highly probable. In Europe the integration of zooarchaeological and genetic evidence provides a pattern that is compatible with a blend of introduced and local domestication (Albarella et al. 2006). Southeast Asia hosts several other wild *Sus* species, and the possibility that at least one of these also could have been domesticated has been raised (Groves 1981), though current scholarship has questioned this.

After its initial domestication(s) pigs became widespread in Eurasia and Africa, but they did not reach the Americas until the arrival of the Europeans in the fifteenth century. They probably reached Oceania from South-East Asia, but the form and timing of this event is still debated.

One of the problems in identifying the emergence of domestic pigs concerns the difficulty in separating the archaeological remains of wild boar and domestic pigs. This is an issue that affects all periods, but particularly the earliest stages of domestication, when wild boar and domestic pigs were morphologically still very similar. It has been suggested that morphological changes—at least those that can be perceived archaeologically—only emerged well after the earliest onset of the domestication process. Of these changes the most obvious is a reduction in body size, but a relative shortening of the snout and a decrease in sexual dimorphism have also been observed. To detect domestic pigs in the archaeological record it is important to consider, in addition to morphometry, multiple lines of evidence, including age profiles, sex ratios, and genetics. Isotopes can inform us on feeding regimes, which may have differed between the two forms. In the Mediterranean, Southeast Asia, and the Far East considerations have also been based on the occurrence of pigs on islands previously devoid of wild boar. Logically this should suggest that the pigs were imported there by people. However, wild boars are strong swimmers

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and, in some cases, they may have arrived on these islands independently.

Our ability to separate wild boar and domestic pigs hinges on the degree of physical—and consequently genetic—separation between the two forms. The extent to which such separation will occur is dependent on the adopted husbandry strategies. In the past, free-range pig herding was common, and this would generate domestic pigs with morphological characteristics that are not very different from those of the wild boar. These pigs would be subjected to many of the same adaptive pressures that characterize the wild boar (e.g., the retention of long snouts to allow digging for products such as roots and tubers). Additionally, free-range pigs could readily interbreed with wild boar, therefore generating a genetic and morphological continuity between the two populations. Free-range pig-keeping must have been the norm in prehistoric times—it has the advantage of low labor requirements as pigs can thrive even without human support. Yet, changes identified in several geographic areas suggest that between the Early and Late Neolithic the degree of separation between wild and domestic forms increased, probably as a consequence of greater human control, including enclosure. This trend continues in the metal ages, at least in Europe. The drift towards size reduction, which began with the initial domestication, largely continues until the end of the prehistoric period. The smallest domestic pigs are found in the Bronze and Iron Ages, before the “improvements” that characterize the historical periods.

The Romans made deliberate attempts to improve farm animals, and pigs were no exception. Several breeds are known from Roman written sources, and archaeologically both large and small morphotypes have been recognized in Italy. The small breeds remained the most popular, perhaps because they were more mobile and easier to drive towards urban centers. The larger pigs were probably mainly used for sacrificial purposes as the iconography of the time suggests (MacKinnon 2001). Although pork was the preferred meat in Roman Italy, this was not the case in other areas of the Roman Empire, where beef and mutton were more commonly consumed.

In the Middle Ages pigs could be kept enclosed or free range according to the husbandry culture of the time and area. The taxation system known as “pannage,” allowing for the pasturing of free-range pigs in the forest, is particularly well known in England, but similar practices occurred elsewhere. In later medieval times and in the modern period, pigs could also be found roaming town streets (often causing a nuisance). The single sty-pig, generally confined to the backyard of a house, is, however, an almost exclusive modern phenomenon. It is this practice that led to the creation of the fat, large, pink, and fairly hairless pig that typically characterizes the contemporary image we have of the animal.

Unlike other farm animals, pigs do not provide secondary products, such as wool or milk, and are generally exclusively raised as food providers. Even the skin is most typically used as food, though it could occasionally serve other purposes, such as in footwear. An interesting exception is represented by black Korean pigs, which used to have their sties associated with human toilets. They fed (partly) on human excrements, therefore also fulfilling an important cleansing role. Such practice also occurred in China during the Han dynasty (300 BCE to 300 CE), as attested by numerous figurines, typically funerary models, recovered from archaeological sites.

The sty-pig has in the contemporary world become confined to traditional rural areas, while the most common form of pig breeding is through intensive factory farms, raising both environmental and animal welfare concerns.

Free-range pigs can, however, still be found in many parts of the world. The pigs of Papua New Guinea have famously been discussed in the ethnographic literature, but free-range pigs are also known from other areas, such as South Asia, the Caucasus, the Balkans, Iberia, and several Mediterranean islands. They tend to provide products of much greater quality than the intensively reared pigs, and have a much smaller environmental impact. Because of their lifestyle these pigs are slim, often small, and highly mobile (Figure 1). In Sardinia, pig transhumance was practiced until a few decades ago and the practice is also known, through literary sources, in medieval France and Spain (Albarella, Manconi, and Trentacoste 2011). The



Figure 1 A free-range pig from Sardinia.
Source: Photo by Umberto Albarella.

possibility of long-distance pig herding in prehistory has been raised on the basis of isotopic evidence (see ZOOARCHAEOLOGY AND STABLE ISOTOPES).

Pork is and has been consumed all over the world, and it has a particular prominence in East and Southeast Asia. It is, however, *not* eaten in Islamic and Judaic societies. This food avoidance is long-standing and has been documented archaeologically. Though some archaeological sites associated with Muslim and Jewish cultures are indeed entirely devoid of pig bones, others are not, which suggests that this food taboo was not always strictly followed.

Pig meat was not only a source of nourishment; in many societies it also played an important social and ritual role. Pigs are the quintessential feasting animals as they have a high reproductive rate. They can be sacrificed in large numbers without jeopardizing the herd. Feasting events heavily based on pork consumption have been recognized at several prehistoric and historic archaeological sites.

Pigs have also been associated with rites of fertility. Their fecundity makes them ideal for this role. Piglet bones are frequently found in ritual contexts, often burnt. The practice is well known—through iconography, history, and archaeology—for the Romano-Greek world as well as in prehistoric caves. The most famous use of pigs in classical rituals is through their association with the myth of Demeter and Persephone, attested both historically and archaeologically.

Pigs have enriched life on the planet and have accompanied human societies in their journey through more than 10,000 years of history. They have supplied proteins but also company and inspiration. They represent a regular feature in many works of art, poetry, and literature. People should not forget the debt of gratitude they owe to pigs and that the mistreatment of these animals is not only ethically despicable but also an insult to the rich history that characterizes our relationships with these remarkable animals.

SEE ALSO: Companion Animals;
Domestication; Zooarchaeology;
Zooarchaeology and Ancient DNA

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Pollution and Heritage Conservation

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For as long as humans have been creating cultural heritage there has been a risk of damage from pollution. In our quest to preserve heritage, we must recognize and manage the risks to artifacts that we want to protect. The effects of pollution are as varied as types of cultural heritage. Sources and types of pollutants are numerous. In order to identify the threat of pollution to heritage it is important to understand the material composition of that heritage.

A pollutant is a substance that has a detrimental effect on the environment or on something of value, and is present in the atmosphere in amounts greater than the natural concentrations, primarily due to human activity. Heritage can be threatened by outdoor pollutants, such as gases and particles from vehicle exhaust. Outdoor pollutants can make their way into buildings and can affect heritage inside museums. Artifacts indoors are also threatened by pollutants generated from sources within, such as fumes from cleaning products.

The types of pollution that can threaten heritage depend on the activities within the meteorological range of the site. Major outdoor sources of pollution include natural sources, agriculture, atmospheric reactions, industrial processes, and vehicles. The geography of the site and the weather patterns can determine the pollution matrix at a heritage location. Indoor air quality can be affected by outdoor air quality that infiltrates the building. Once inside, the indoor air quality is a function of the types of heating, ventilation, and air conditioning systems, processes and activities within the building, and materials used within the space. Major indoor sources are combustion (cooking, smoking, heating), materials off-gassing, gas-phase reactions, cleaning solutions, and human activity. A

pollutant can be a gas, liquid, or solid. Pollution and heritage conservation is usually concerned with airborne particles and gases.

Particles can be composed of carbon, alkaline materials, silicas, salts, metals, and so on. They can be visually intrusive, abrasive, or sites for chemical reactions. Particles are recorded as the number or weight of particles at a specific size in micrometers (μm). Typical sizes reported are PM10 or 10 μm , PM2.5 or 2.5 μm , and PM1 at 1 μm . Additionally, we now must consider the adverse effects of nanoparticles, which have increased in number with combustion engine improvements. These smaller particles are difficult to keep out of environments.

Gaseous pollutants can be generated indoors and outdoors. Typical outdoor pollutants are sulfur dioxide (SO_2), nitrogen oxides (NO , NO_2), reduced sulfur compounds such as hydrogen sulfide (H_2S), carbonyl sulfide (COS) and carbon disulfide (CS_2), ammonia (NH_3), and peroxides like ozone (O_3). There are also indoor sources of these chemicals (Grzywacz 2006). Indoor pollutant compounds number in the hundreds. Several are recognized as threats to heritage: organic carbonyl pollutants, specifically formaldehyde, formic acid, acetic acid, reduced sulfides, ozone, amines (R-NH_2), and volatile organic compounds (VOCs). The small-molecule organic carbonyl pollutants are known to be a risk because analysis of corrosion products on artifacts has identified acetates and formates.

Gases are measured volumetrically in parts per billion (ppb) or weight per volume of air, micrograms per cubic meter ($\mu\text{g}/\text{m}^3$). The concentrations that pose a risk to heritage are usually in the ppb or $\mu\text{g}/\text{m}^3$ range, whereas human health concerns are usually a thousand times more concentrated at parts per million (ppm or mg/m^3). These are very small levels. One ppb is equivalent to one yellow ball in a line of one billion white ping-pong balls that it would take to wrap around the equator of the earth.

Which pollutant/contaminant is a risk to the preservation of heritage resources is dependent upon the materials of the artifact. To understand the risks, the conservator must know the

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materials. Grzywacz (2006) recommends target levels for gaseous pollutants in museum environments. Current concentration limits are based on limited empirical evidence of visible damage and known concentrations. Health guidelines are used as starting points, because regulations are available. Natural background levels and urban levels are used as a reference for what concentrations are achievable.

Damage from pollution is a function of the sensitivity of the material(s), the exposure time, and pollutant concentration. A large amount of a pollutant in an environment with a susceptible material or artifact will likely result in visible damage in a short time. A low concentration can also be a risk over a long period of time. Hatchfield (2002) and Tétreault (2003) recommend strategies to mitigate pollution for heritage conservation. *ASHRAE Handbook–HVAC Applications*, chapter on “Museums, Galleries, Archives and Libraries,” is reviewed every four years and includes a section on airborne pollutants, target levels, and risk to heritage.

SEE ALSO: Air Pollution; Chemistry in Archaeology; Conservation; Conservation Science; Deterioration; Environment and Landscape; Measurement Theory; Preventive

Conservation in Archaeological Sites; Urban Environments; Water Pollution

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Potatoes

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Paleoethnobotanists study plant macro- and microremains from archaeological sites in order to understand the subsistence strategies of ancient societies, and the environmental conditions prevalent at that time. Paleoethnobotany (see PALEOETHNOBOTANY) also guides botanists and plant taxonomists in their search for the centers of origin and domestication of useful plant species. These two objectives are closely related due to the evolution of plant species over time. Basically, most of the cultivated plants currently known are not the same plants that *Homo sapiens* encountered in the territories that they colonized during the Late Pleistocene or Early Holocene epochs. Most of the existing cultivated plant species are the product of natural or controlled hybridization of genetically compatible wild species, followed by natural (environmental) or human-mediated selection (see DOMESTICATION).

The potato that became the world's third-largest food crop is genetically different from the original potato that once emerged in the center of origin of this species (*Solanum tuberosum*) in southern Peru, South America. In fact, *S. tuberosum* was unknown to the Old World and even outside South America in ancient times. Yet, many wild, tuber-bearing potato species existed from central Chile and Argentina to the southwestern United States before the arrival of *H. sapiens* in the Americas. Interestingly, Mexico is considered one of the two centers of genetic diversity of wild potatoes, even though potatoes were never cultivated or consumed in Mexico or Mesoamerica in pre-Hispanic times. The point is that the potato has an extremely large secondary gene pool of different but related species, mainly in its primary center of diversity in the Andean region of South America. Following the latest taxonomic proposal, 110 tuber-bearing potato species are listed in the genus *Solanum* section *Petota*; and three nontuber-bearing potato species are

assigned to the section *Etuberosum*. This extreme genetic diversity and, yet, morphological similarity of many wild and cultivated potatoes has been the nemesis of even the most experienced potato taxonomists in the world. Considering the difficulties faced by expert taxonomists having access to extant potato germplasm collections, well-maintained plant herbaria, and molecular tools to study plant systematics, it is possible to understand the challenges encountered by archaeologists trying to identify ancient remains of unknown potato species.

The site of "Monte Verde" in southern Chile, South America, is probably the most famous archaeological landmark in the Americas. This site pre-dates by over 1,000 years the equally archetypal site of "Clovis" (dated to about 13,000 BP) in New Mexico, the United States, originally considered the epicenter of the first group of Native American hunters and gatherers in the New World. Moreover, Monte Verde yielded many interesting macrobotanical samples, including potato tuber skins (Dillehay 1989). The presence of "potato" in Monte Verde had important implications. First, it is the earliest archaeological record of "potato" in the Americas; second, the most widely cultivated potato in the world (the Chilotanum group of *S. tuberosum*) originated about 80–300 km southwest of Monte Verde (from Chiloe Island to the Archipelago of Chonos and Guaitecas); and, third, it rekindled peer discussions on the origin of the common potato cultivated in the temperate zones of the world, where only the long-day (or short-night) varieties of *S. tuberosum* became adapted, as in southern Chile.

The original taxonomic analysis of the potato remains found at Monte Verde indicated that they belonged to the wild species *Solanum maglia* (Ugent, Dillehay, and Ramirez 1987). This species is the only tuber-bearing wild potato known in the southern temperate zone of South America. However, further analyses of the starch grains of extant *S. maglia* samples (Spooner et al. 2012) showed various inconsistencies in the interpretation of the botanical results obtained at Monte Verde. Furthermore, *S. maglia* is found about 1,000 km north

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of this archaeological site. The archaeologists of Monte Verde also suggested that *S. maglia* was a staple food of the Paleo-Americans that occupied that southern region, but *S. maglia* is known to contain very high levels of toxic glycoalkaloids, which make its tubers not only very bitter but also poisonous, even after cooking. This confusion may have arisen from the general name “*malla*” given to “native potatoes” by the Mapuche people encountered by the first European chroniclers, later Latinized as *maglia*. However, the edible native potatoes grown by the Mapuche were probably introduced into southern Chile from Peru, Bolivia, or Argentina during the Late Archaic period, or possibly even later (ca. 2,500 BP) by migrant Mapuche groups from south-central Chile or southwestern Argentina.

The role of *S. maglia* as a possible progenitor of the Chilotanum group of *S. tuberosum* potatoes has been investigated with mixed results. Whereas potato taxonomists believe that *S. maglia* was not closely involved in the development of the long-day potato varieties of southern Chile (Chilotanum group), *S. maglia* was found to be phylogenetically related to this group of potatoes. Moreover, this molecular research definitely showed that the Chilotanum potatoes from southern Chile gave origin to the potato varieties grown in the temperate zones of the world. The Chilotanum potatoes were derived from the central Andean (Andigenum) *S. tuberosum* potatoes of southern Peru by further hybridization with a wild potato species (possibly *S. tarijense*), encountered as the Andigenum genotypes were disseminated into Chile through the Andean region of Bolivia and northwestern Argentina. These two groups, Andigenum and Chilotanum, constitute the *S. tuberosum* species of potato cultivated all over the world.

The paleoethnobotany of *S. tuberosum* in its center of origin (Peru) is rather limited (Ugent and Ochoa 2006) and debatable. The earliest potato remains were found at the site of “Tres Ventanas,” a group of three caves located at 3,925 m above sea level in the Chilca Canyon, 65 km southeast of the capital Lima. The caves were occupied from about 10,000 to 6,000 BP, during the Archaic period. Human, animal, and plant remains were found at different levels spanning over 9,000 years, with the potato samples dated to about 6,900 BP (initially dated to 10,000 BP).

Considering their age and the fact that the site is located in a very high and dry area, it is possible that these potato remains belonged to a wild potato species. The remaining archaeological sites where potato remains have been detected in Peru are dated to the Late Archaic period (4,000–3,200 BP), and are located on or close to the dry Pacific coast of Peru, where potatoes are not grown at the present time. This observation shows a tendency for the earliest macrobotanical remains of potato to be located predominantly in dry areas, where they were probably acquired and preserved, rather than cultivated. For instance, the coastal Casma Valley is formed by the basin of the Casma River, which flows across the coastal desert of the Ancash region of Peru. There, four archaeological sites—“Huaynuma,” “Pampa de las Llamas,” “Tortugas,” and “Las Haldas”—dated between 4,250 and 3,200 BP, yielded potato remains. The presence of potatoes and some cultivated plant species at these desert sites suggests that the potatoes found were already cultivated in more fertile regions of the nearby Andean mountain range. In the same Late Archaic period, the site of “El Paraíso,” located in the Chillón River Valley on the central coast of Peru, also contained potato remains dated to about 4,200 BP. In this case, the fertile Chillón valley could have supported potato production along its middle and high basin course, located 1,000–4,300 m above sea level. The remaining archaeological sites where potato remains or ceramics depicting potatoes have been found are also located along the arid Pacific coast of Peru, where cultivated potatoes (*S. tuberosum*) could have been imported from the bordering mid-altitude zones of the Andean mountains during the Current Era.

Modern cladistic analyses show that the Andean *S. tuberosum* landrace populations form a monophyletic clade, derived from the southern Peruvian members of the *S. brevicaulis* or *S. bukasovii* complex (Spooner et al. 2005), distributed mainly in the Pasco, Junín, Huancaavelica, Ayacucho, Cusco, and Apurímac regions of Andean Peru. The latest molecular taxonomy currently includes previously recognized species such as *S. chaucha*, *S. phureja*, and *S. stenotomum* in the *S. tuberosum* complex, which makes their identification in microbotanical studies more challenging. The new potato taxonomy proposal only recognizes three other cultivated

hybrid species of “bitter potato”: *S. ajanhuiri*, *S. juzepczukii*, and *S. curtilobum*. These species are usually cultivated at altitudes between 3,600 and 4,300 m above sea level in the Central Andes. The bitterness of these potato species is due to their high concentration of toxic glycoalkaloids, a defense mechanism against pests in general. Due to this trait and the fact that bitter potatoes possess a higher tolerance to frost damage than *S. tuberosum*, they cover about a third of the area planted to potatoes in the Peruvian and Bolivian altiplano. Bitter potatoes are transformed into edible products (“chuño” and “tunta”) by an ingenious natural process of freeze-drying practiced by early societies in the New World.

The bitter potato species *S. ajanhuiri* was formed by natural hybridization between *S. tuberosum* Andigenum and the wild potato species *S. megistacrolobum*. The latter species is distributed mainly in the Bolivian departments of La Paz, Cochabamba, Potosi, Chuquisaca, and Tarija at elevations between 3,700 and 4,100 m. *Solanum juzepczukii* was formed by hybridization of *S. tuberosum* Andigenum and the wild potato species *S. acaule*. This wild progenitor is distributed throughout the highlands of central Peru, but its populations are concentrated south of Lake Titicaca, in the Bolivian departments mentioned above. *Solanum curtilobum* was probably obtained from a cross between *S. tuberosum* Andigenum and *S. juzepczukii* (Spooner et al. 2007). Although the origin of these bitter potatoes indicates that these hybrid species were formed after the cultivated Andean potatoes of southern Peru, their center of origin seems to be located south and not north of Lake Titicaca, as *S. tuberosum* Andigenum.

The most important agricultural complex on the southern shores of Lake Titicaca was “Chiripa” (ca. 3,600 BP), considered the foundation of the first “Cultural Empire” in the Central Andes: “Tiwanaku.” This society expanded its dominion and influence north and south of the circum-Titicaca area, and contributed to the expansion of the Tiwanaku–Huari empire (1,500–1,000 BP) from northern Peru to northern Chile. The Huari tradition owes its development to the “Huarpa” culture (2,200–1,500 BP), one of the earliest agricultural complexes in southern Peru. The Huarpa integrated numerous farming settlements around

their capital “Nahuimpuquio,” and started the construction of agricultural terraces and hydraulic works in the highlands to incorporate the mountains of the steep Andean region into agriculture, over 1,500 years before the Inca emerged in Peru. The Andean potato may have been domesticated during the Archaic period of Peru (8,000–3,800 BP), but the existing archaeological evidence suggests that extensive potato cultivation in the Central Andes only took place in the Early Formative period (3,800–3,000 BP). Potatoes were widely cultivated in South America when the Spanish conquerors and chroniclers first arrived and saw potatoes in the central highlands of Colombia in 1537; in northern Ecuador in 1538; in Peru in 1539; in the circum-Titicaca area in 1552; and in the Guaitecas archipelago of southern Chile in 1557.

SEE ALSO: Domestication; Paleoethnobotany; Starch Granule Analysis

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Rice

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Rice refers to the cultivated grass species *Oryza sativa* (Asian rice) and *Oryza glaberrima* (African rice). As a staple food for over half the world's population, it is the predominant dietary energy source for 17 countries in Asia and the Pacific, nine countries in North and South America, and eight countries in Africa. Rice is the most important cereal grain with regard to human nutrition and caloric intake (Smith 1998). According to a report of the Food and Agricultural Organization of the United Nations in 2004, rice provides 20 percent of the world's dietary energy supply, while wheat supplies 19 percent and maize 5 percent.

Rice is normally an annual plant, but it can be grown as a perennial crop in tropical areas. Rice growth is relatively rapid. Rice can complete the process of germination, flowering, and fruiting within three to four months. A normal growth period lasts around 130–140 days, though a life cycle spanning a year is also possible. Therefore, it is possible to grow three crops of rice per year in some warm areas.

Rice cultivation is suited to countries and regions with high rainfall, as it requires ample water. However, rice can be grown practically anywhere, even on steep hills and in mountain areas by using water-controlling terrace systems, such as those in the Guangxi and Yunnan Provinces of South China. Although its parent species are native to Asia and certain parts of Africa, centuries of trade and exportation have made rice commonplace in many societies worldwide.

Traditionally, farmers plant young rice seedlings after controlled flooding of the fields. This method requires sound planning and the use of water dams and channels, but deters vermin and reduces the growth of less-robust weeds

which cannot grow underwater. Although flooding is not necessary for the cultivation of rice, all other means of irrigation require greater weed and pest control during the growing season and a different approach to fertilize the soil.

Rice plants can grow to 1–1.8 m tall, depending on the variety and soil fertility. They have long, slender leaves, which when young are very similar to some weeds. Farmers generally distinguish them based on the special auricle and ligule on the leaf. The small flowers are produced in a branched arching to pendulous inflorescence 30–50 cm in length. The panicle contains about 200–300 flowers, with each flower producing a single edible caryopsis. The grain is between 5 and 12 mm in length and 2 and 3 mm in breadth. Rice is wind pollinated or self-pollinating.

Early, mid-season, and late-season forms of rice have been developed which respond differently to day-length. The early, mid-season rice is insensitive to light, and will normally reach maturity regardless of when it is planted. Late-season rice is much more sensitive to day-length. It requires short day-length conditions to complete heading and grain filling. As such it is very similar to wild rice from which it is directly evolved.

Rice is generally cultivated in the paddy fields, but dry rice cultivation in upland areas is also practiced. The morphological difference between water- and land-grown rice is small, while the physiological difference is relatively large. Dry-grown rice produces lower yields but is adapted to grow with the minimum amount of water. Its stem and leaf are strongly heat resistant, and its developed root system is adapted to low water availability.

Paddy rice is usually harvested when the grains have a moisture content of around 25 percent. Harvesting can be carried out by the farmers themselves, but is also frequently done by seasonal labor groups. Harvesting is followed by threshing, either immediately or within a day or two. Subsequently, paddy rice needs to be dried to bring down the moisture content to no more than 20 percent to make it ready for milling.

Cooked indica rice is dry and loose, and suitable for making rice noodles, fried rice, and radish patties. The cooked japonica rice is sticky, and good for general use. However, both indica and japonica rice produce glutinous grains. The indica glutinous rice is slender in appearance, while the japonica glutinous rice is short and round. Both of them are white and opaque in color. The indica glutinous rice is usually used for making eight-treasure porridge and rice dumpling, and the japonica glutinous rice for wine and rice pudding.

Rice wine, also known as *mijiu* in Chinese, is an alcoholic drink made from rice, which is traditionally consumed at formal dinners and banquets, and used in cooking as well in Asia. It is also used within a religious and ceremonial context. Rice wine is made from the fermentation of rice starch that has been converted to sugar. Microbes are the source of the enzymes that convert the starches to sugars. Rice wine typically has an alcohol content of 18–25 percent alcohol by volume. Chinese alcohol predates recorded history. Dried residue (see ORGANIC RESIDUE ANALYSIS) extracted from a 9,000-year-old pottery at Jiahu site in east-central China implies that early alcoholic beverages made from rice, honey, grapes, and hawthorn were already being consumed by the Neolithic peoples.

Indica rice and japonica rice are the result of long-term adaptation to different ecological conditions, in particular temperature. Indica rice is mainly found in tropical and subtropical lowlands. It can tolerate both high temperatures and strong light levels. The grains are slender and nonsticky, and similar to wild rice. Therefore, it is considered to be the basic cultivated form, evolved directly from wild rice. Japonica rice has a wide distribution, typically in mountainous and temperate regions. It can tolerate cold and low light levels. The grains are short and round, as well as sticky. It is thought to have developed from indica rice.

There have been plenty of theories concerning the origins of domesticated rice in Asia. Some early suggestions considered that Asian rice was most probably first domesticated in an area between Assam in India to Yunnan Province in China, but evidence for this is still lacking. Genetic evidence shows that all forms of Asian rice, both indica and japonica, sprang from a

single domestication of the wild rice *Oryza rufipogon* that occurred 8,200–13,500 years ago in South China (Molina et al. 2011). Mapping rice genome variation suggests that this domestication occurred in the Pearl River valley region of China (Huang et al. 2012).

The increasing amount of data on early rice farming in the middle and lower reaches of the Yangtze River in China means that this region has become one of the most important places to trace the origin and development of rice agriculture (Normile 1997). Morphological studies of rice phytoliths (see PHYTOLITH ANALYSIS) from the Diaotonghuan archaeological site in the middle reaches of the Yangtze River show a possible transition from collecting wild rice to cultivating domesticated rice. A large number of wild rice phytoliths in a layer dating from 12,000–11,000 years ago indicates that wild rice collection was part of the local means of subsistence. Morphological changes of phytoliths recovered from layers dating from 10,000–8,000 years ago show that rice had by this time been domesticated (Zhao 1998).

The initiation of rice agriculture is believed to be linked to the establishment of more or less sedentary settlement patterns and the occurrence of pottery making. The warming climate after the last glaciation allowed the spread of wild rice northward, while a growing human population with increasing food requirements and the ability to store foodstuffs would have provided the right conditions to promote domestication (see DOMESTICATION). Evidence from the middle and lower Yangtze River area exhibits the transitional process from a hunting and gathering society to an agriculture-oriented society (Wang et al. 2010).

About 5,000–4,000 years ago, there was a rapid expansion of rice cultivation into mainland Southeast Asia, eastwards to the Korean Peninsula and the Japanese archipelago, and westwards across India and Nepal. Rice spread to the Middle East about 2,000 years ago. Rice was introduced to Europe through western Asia, and to the Americas through European colonization.

Oryza glaberrima, known as African rice, is native to West Africa. It is believed to have been domesticated from its wild ancestor *Oryza barthii* in the inland delta of the Upper Niger River some 2,000–3,000 years ago. The genome

of *O. glaberrima* has been sequenced (Wang et al. 2014). At present, African rice is being replaced by the introduced Asian rice. Some West African farmers, including the Jola of southern Senegal, still grow African rice for use in ritual contexts (Linares 2002).

African rice grows best on fertile alluvial soils, although it tolerates low soil fertility and can produce higher yields than Asian rice on alkaline and phosphorus-deficient soils. African rice is generally more tolerant to fluctuations in water levels, iron toxicity, infertile soils, severe climatic conditions, and human neglect, and exhibits better resistance to various pests and diseases than Asian rice. However, the grains are harder and shatter more easily than those of Asian rice. This means that African rice is less easily milled.

African rice was introduced to the New World during the days of the slave trade, and today is cultivated in parts of Brazil, Guyana, El Salvador, and Panama. African rice is still an important crop for small-scale farmers, who grow it for its nutty flavor and other culinary qualities. It is also used in rituals and in African traditional medicine.

By cross-breeding different kinds of rice, the earliest high-yield rice was cultivated by an American plant breeder, Henry M. Beachell, in 1966. But it was not until 1974 that the first hybrid rice varieties were released by a Chinese hybrid rice breeding expert Longping Yuan. As with other types of hybrids, hybrid rice typically displays heterosis or hybrid vigor so that it can produce up to 30 percent more rice when it grows under the same conditions as comparable high-yielding inbred rice varieties. Scientists from the Africa Rice Center managed to cross-breed African rice with Asian rice varieties to produce a group of interspecific cultivars called New Rice for Africa. Nowadays, high-yield crops, like hybrid rice, have become one of the most important tools for combating world food crises.

Genetically modified rice comprises rice strains that have been genetically modified. Rice plants have been modified to increase micronutrients such as vitamin A, accelerate photosynthesis, tolerate herbicides, resist pests, increase grain size, generate nutrients, improve flavors, or produce human proteins (Sharma and Sharma 2009). The natural movement of genes across species, often called horizontal gene transfer or lateral gene transfer, can also occur

with rice through gene transfer mediated by natural vectors. However, the cultivation and use of genetically modified varieties of rice remains controversial.

SEE ALSO: Archaeological Record; Human Growth and Development; Maize; Paleoenvironmental Reconstruction; Paleoethnobotany; Palynology; Wheat

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River Systems

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Rivers provide arteries of varying scale, allowing freshwater, sediments, and soluble elements to move from terrestrial uplands to the seas, thereby completing the hydrological cycle. Rivers are usually visible landforms on the earth's surface, but in soluble geologies such as limestone, or within glacial environments (see GLACIAL AND PERIGLACIAL ENVIRONMENTS), they can flow beneath it. On the surface, they may be constrained within narrow valleys where they inundate entire floodplains, or they may occupy wider valley floors, only part of which is subject to active river processes at any one time. The former courses of subterranean rivers can produce caves and fissures (see CAVES AND FISSURES) that provide important foci for subsequent occupation by both humans and animals and preserve sedimentary sequences (Woodward and Goldberg 2001), which allow paleoenvironmental reconstruction (see PALEOENVIRONMENTAL RECONSTRUCTION). In semi-arid and arid environments, ephemeral rivers occupy valleys known in the Middle East and North Africa as wadis, but they are only active after significant rainfall causes flooding (see FLOODING).

Water is essential for all life and rivers have provided resource-rich environments and corridors for animal and human migration since the earliest hominins emerged in East Africa around 4 million years ago. As modern humans moved from mobile, subsistence strategies to those focused around more sedentary agricultural lifestyles, the fertile plains of major systems, such as the Indus River, Yellow River, Nile, and Euphrates, became the birthplaces of ancient societies. Where water sources are scarce, humans have constructed irrigation systems linked to rivers to harvest floodwaters (Meister, Rettig, and Schütt 2016). As societies became ever more sophisticated, rivers and associated wetlands developed as

important foci for ritual and religious activity, including the votive deposition of objects (see BEHAVIORAL ARCHAEOLOGY). Since later prehistory, rivers have been a conduit for the trade and exchange of goods, which accelerated during the historic period. With economic growth came increasing river engineering, notably to harness water power and improve navigation and trade links.

Rivers are natural conveyors of, and sinks for, sediment and biological remains, and, as such, can form significant paleoenvironmental archives. Their energy levels and ability to transport sediment are governed by internal factors such as bed friction and channel gradients, as well as external factors such as climate and sediment supply. Historically, high water tables in valley floors globally have helped create anoxic environments where cultural and environmental remains can be well preserved within peat deposits (see PEAT DEPOSITS) or other fine-grained sediments, for example, causeways, platforms, trackways, and fishweirs. Such preservation provides opportunities for detailed paleoenvironmental reconstruction of climate, vegetation, and anthropogenic activity, using, for example, palynology (see PALYNOLOGY), chironomids, paleoethnobotany (see PALEOETHNOBOTANY), and archaeoentomology (see ARCHAEOENTOMOLOGY). However, intense pressure on contemporary groundwater resources via abstraction is resulting in the degradation of these fragile environmental resources, although hydrological modeling (see HYDROLOGICAL MODELING) can help to assess the potential for long-term preservation in situ.

Rivers also provide important records of pollution (see WATER POLLUTION) evidenced in the archaeological record through geochemical analysis of contaminated sediments associated with the mining of metalliferous ores. In northern Europe, the majority of historical contamination is associated with the industrial revolution (Audry et al. 2004), whereas elsewhere, for example the Levant, significant pollution records extend back into prehistory (Grattan, Gilbertson, and Hunt 2007).

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The long-term evolution of river systems is underpinned by climatic cycles and geological uplift histories, the latter associated usually with tectonic or glacio-isostatic processes. During the Pleistocene epoch of the Quaternary timescale and the period associated with Paleolithic human activity, evidence of former river systems beyond the limits of icesheets is usually preserved as terrace sediments and associated surfaces, each representing a former floodplain subsequently isolated by fluvial incision. Each terrace provides a record of both erosion and sedimentation associated with discrete glacial–interglacial cycles, driven by astronomical changes in the earth’s orbit around the sun. These astronomical cycles and the aggraded river terraces can be correlated with oxygen isotope chronostratigraphy established within deep-sea sediments, thereby allowing global correlation of climatic periods and fluvial archives (Bridgland, Maddy, and Bates 2004).

Dating of Pleistocene terrace deposits is largely beyond the limits of radiocarbon techniques and usually relies on other methods. These comprise primarily: (1) the stratigraphic relationship, sedimentology, and altitudinal position of terrace deposits with respect to each other; (2) the identification of discrete faunal and floral assemblages within terrace sediments (see QUATERNARY LARGE-MAMMAL ZONES and QUATERNARY MICRO-MAMMAL ZONES); (3) the use of other absolute or relative dating techniques that estimate either the age of the sediments themselves or associated faunal remains, for example, optically stimulated luminescence (see OPTICALLY STIMULATED LUMINESCENCE), cosmogenics (see COSMOGENIC DATING), amino-acid racemization, and electron spin resonance (see DATING AND ELECTRON SPIN RESONANCE (ESR)). In tectonically active regions, the dating of lava flows interbedded within terrace sequences using isotopic techniques has also provided significant results. Until the 1970s, terrace chronologies were commonly dated by lithic artifact associations (see DATING (BURNT) LITHICS), though it is now recognized that such robust artifacts can be reworked through numerous terrace units, therefore requiring cautionary use (Bridgland and White 2015).

In northern and southern latitudes during glacial cycles, erosion and sedimentation within river valleys beyond extensive icesheets was

characterized by the deposition of sands and gravels within unstable, multichanneled braided systems. There was little in the way of organic sedimentation, reflecting the sparse vegetation cover, but aeolian activity often led to the reworking of sands and silts, which blanketed terrace surfaces with coversand and loess. Where permafrost was present, periglacial processes led to the development of ice wedges and cryoturbated horizons within the deposits. While organic sediments are sparsely preserved, they have the potential to provide insights into paleoecology and paleoenvironments.

During interglacial stages, sedimentation in northern and southern latitudes was characterized by deposition of silts, clays, and organic sediments (peat, gyttja) in single (meandering) or multichanneled (anastomosing) systems, reflecting stable, well-vegetated environments (see TEMPERATE ENVIRONMENTS). Such sediments can occur as discrete channel fills or as more widespread overbank deposits. The abundance of vegetation and generally low-energy conditions afford significant opportunities for environmental reconstruction.

Throughout the Paleolithic, hominins were hunter-gatherers, leaving little trace of their temporary encampments or evidence for their exploitation of environments. It is generally believed that hunter-gatherer groups spread more extensively into the northern and southern hemispheres during interglacials, often via river systems, whereas during glacials they retreated towards warmer refugia and favorable niche areas of southern Europe and the equator. During glacials, migration extended onto continental shelves that became dry-land as a consequence of icesheet expansion and globally lower sea levels; these now-submerged landscapes would have had their own network of rivers (Bicket and Tizzard 2015).

Buried within and upon river terrace deposits, the primary evidence of Paleolithic human activity usually comprises isolated finds or more abundant assemblages of stone tools, found by a variety of archaeological fieldwork, particularly where aggregate quarrying has been monitored for Paleolithic archaeology. Very rarely, terrace sediments have yielded extensive, well-preserved evidence for animal butchery on

former floodplains, as at Lynford in the United Kingdom (Boismier, Gamble, and Coward 2012).

For the last 10,000 years of geological time, an interglacial climate has prevailed, and for the first few thousand years the landscape developed naturally without significant anthropogenic interference. In northern and southern latitudes, temperate climates resulted in environments akin to those prevailing during earlier interglacials, providing rich resources for Mesolithic hunter-gatherers. The development of more sedentary lifestyles associated with farming in later prehistory led to deforestation of landscapes, resulting in soil erosion and colluviation; this, in turn, overloaded river systems with fine-grained sediment and resulted in alluviation (Brown 2009). Indeed, the thick alluvium of modern-day floodplains has no Pleistocene interglacial analog. Across Europe, statistical analyses of radiocarbon dates associated with Holocene river sediments have allowed episodes of erosion and alluviation to be correlated with climate change, with the greatest effects identified when humans have made landscapes susceptible to erosion through agricultural activity (Macklin, Jones, and Lewin 2010; see EROSION).

Elucidating the evolution of river systems and dovetailing knowledge of the associated archaeological record is best achieved using frameworks designed around geoarchaeology (see GEOARCHAEOLOGY) and geomorphological survey (see GEOMORPHOLOGICAL SURVEY). Geoprospection for Paleolithic remains requires a detailed understanding of Quaternary sedimentary records and formation processes (see FORMATION PROCESSES) due to the low population densities and hence limited impact of hominins on the landscape. In contrast, during the Holocene, human activity and population density increased exponentially, creating complex archaeological records that can only be unraveled using multiple approaches to archaeological fieldwork. During the early part of the twentieth century, geoprospection for postglacial archaeological sites in river valleys developed around the emerging discipline of aerial photography (see AERIAL PHOTOGRAPHY) and set-piece excavation. Now, increasingly sophisticated remote-sensing (see AIRBORNE REMOTE SENSING) techniques are available. These

include a range of multispectral and hyperspectral satellite imagery (see SATELLITE HYPERSPECTRAL AND MULTISPECTRAL IMAGING) and airborne light detection and ranging (LiDAR); terrestrial remote-sensing techniques include geophysical methods such as electrical resistivity (see ELECTRICAL RESISTIVITY) and ground-penetrating radar (see GROUND-PENETRATING RADAR). The sediments themselves also provide opportunities for dating control using a range of radiometric techniques (^{14}C , optically stimulated luminescence (OSL)), as well as opportunities for geochemical and mineralogical analyses to determine catchment erosion and sedimentation histories. Organic sediments preserved within abandoned river channels (paleochannels) and other floodplain wetlands provide further opportunities for environmental reconstruction through the analysis of proxy indicators of past climate, vegetation, and land-use such as pollen, insects, and macroscopic plant remains. However, river evolution has the potential to erode and/or further bury in-situ archaeological remains, affecting visibility and preservation potential (Howard and Macklin 1999).

Understanding the past evolution of river systems, their response to climate change, and how humans have interacted with them, both positively and negatively, is important since it can provide significant insights into how rivers and global societies will respond to future environmental change (Lewin 2012).

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Sampling in Environmental Studies

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Environmental archaeology uses biological materials (pollen, fruits/seeds, wood, bird and mammal bones, invertebrates, etc.) as proxies for interpreting the landscape and economy of archaeological sites. These materials survive to a greater or lesser extent under suitable conditions but, with the exception of some bones and wood, are largely invisible at excavation. Therefore samples of sediment need to be taken and processed for the majority of these remains to be retrieved and studied.

The aim of sampling is to recover a reasonable representation of the remains present in that context. This entry outlines the thought processes involved in sampling, rather than delivering a prescriptive discourse.

The processes in determining a sampling strategy should be the same whether excavation is research-, teaching- or planning-led, although this can be difficult due to time and other resource limitations. It is essential that all project specialists help to develop initial aims and objectives. For example, excavation of an Iron Age farmstead in northern England is planned. The archaeologist is interested in its form and date compared with the large number of other known Iron Age farms in the region—whether it is enclosed, ditched or palisaded, and so on. Given all these other sites, the archaeobotanist knows that the charred plant remains will show use of spelt wheat and hulled barley, probably 6-row, but acknowledges that some samples will need to focus on confirming this (or not). They are interested in the fact that this site lies on a small promontory above an estuary, and would like to explore whether and how these coastal soils were used.

The size and nature of the sample will be determined by what is expected to survive (English

Heritage, 2011, Figure 2; see also FORMATION PROCESSES), as well as the research aims and objectives of the project.

What to sample seems an easy question at first. It could be every suitable context, followed by selecting those to take further once basic phasing (dating) is established, or it might target only those contexts with questions already defined. The first can be time-consuming and costly on a large excavation, although it offers the opportunity to answer new questions that arise as the excavation proceeds. The latter produces samples that should be valuable but is inflexible unless the excavators are aware of opportunities that turn up unexpectedly and act upon these. Other options include stratified systems of sampling every fifth or similar context or, indeed, using a randomized strategy for a mathematically rigorous scheme (see SAMPLING THEORY). Purely judgement samples taken ad hoc may be inappropriate unless a specialist is on-site as, for example, “interesting black material” could easily be coal or manganese on some sites, and of little value in addressing environmental questions. Most often a combination of stratified and judgement methods is used. It is important to sample the full range of context types, including those in areas apparently devoid of activity: those enigmatic “layers” with few or no finds. Evidence of absence can be valuable when investigating spatial patterns.

The next question is whether to process on-site or later in the laboratory. On-site processing with immediate assessment by an appropriately experienced specialist allows feedback and potential modification of the strategy. For example, a pit on an Iron Age site produces a few seeds whose types suggest it might be earlier Bronze Age, so more sediment would increase numbers recovered and reliability of results to test the initial interpretation. Processing later may give better quality control, but is inflexible.

The team will need to decide how much to process. For charred plant remains the aim is to recover at least 100–200 items from a context, although ideally nearer to 500 for statistical analysis. It is quite common to need 40–60 liters of

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sediment to achieve anything near this number for many sites in Britain. In northern England it has been calculated that 1–2 tonnes of sediment would often be needed; clearly this is rarely, if ever, possible or desirable. Thus many samples cannot offer a statistically valid interpretation. However, even small numbers of remains can be used to understand preservation or help to establish presence or absence at a site. These are samples processed by flotation to separate the light fraction of charred plant remains from the heavy mineral component, which itself can produce small bones from mammals, small mammal remains, bird and fish bones, and pot fragments, all of which can easily be missed during hand recovery.

In waterlogged and exceptionally arid deposits, concentrations of plant remains are often higher and 1–2 liters of sediment might well be sufficient to recover sufficient numbers. However, in such deposits the diversity (richness and evenness) of the target population needs to be considered. For example, contexts comprising dung from pastured animals can produce a low diversity of taxa which are undiagnostic or that cannot be identified beyond family level. These samples are processed by washing or dry-sieving them through a bank of sieves down to 250–350 microns in the laboratory.

Monoliths or Kubiena tins are used where intact stratigraphic sequences are needed to look at changes through time: pollen from naturally filled deposits, or from those where dumping may have occurred, like ditches (see PALYNOLOGY). Beetles and macroscopic plant remains are also examined in this way, although monoliths need to be large, with ca. 20 cm sections.

Once samples have been collected and processed, they need assessing as to their potential

to address the initial questions posed, but also to see whether new questions can be asked. It is therefore essential that this stage is undertaken by an experienced specialist who knows the sites and materials of that region for comparison. Full analysis, as then recommended, can be a better way to help train juniors where they can focus on specific samples and questions.

Overall, the three words that should always come to mind with sampling are: *why* sample, *what* to sample and *how* to sample. In this way the most appropriate samples should be taken for the materials expected, the site, and the questions being asked, thereby optimizing use of the available resources.

SEE ALSO: Environmental Archaeology; Formation Processes; Palynology; Sampling Theory

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Sea-Level Change

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Major dimensions of sea-level change

From an archaeological perspective, the main significance of past changes in global mean sea level (GMSL) is the influence on local and regional coastal geography. Consequently, the height of the ocean surface at any given location (relative sea level, RSL) is more relevant to coastal impacts of sea-level change than GMSL. The major causes of regional variability in sea level include climate-related factors (thermal expansion, salinity effects, internal ocean mass redistributions) and non-climatic geological processes (tectonic uplift or subsidence, glacio-isostatic adjustment, sediment compaction), particularly along soft-rock coastlines (Woodroffe and Murray-Wallace 2014). The resultant coastal configuration provides information to help understand changing resource availability over time, the potential for human migration, and coastal and aquatic adaptations, including the development of specialized technologies (Bailey and Parkington 1988).

The global rise and fall of sea level since the last interglacial (~125 ka BP), when sea level was several meters above present (Figure 1), has variously submerged and exposed bridging land masses between continents and islands. In many parts of the world, falls in RSL to 120 or 130 m below present during the last glacial period had a profound influence on the movement of modern humans, such as between Central Asia and North America across “Beringia,” between mainland Europe and the British Isles across “Doggerland,” and between South Asia and Australia, across Sundaland (Harff, Bailey, and Lüth 2016). As the glacial ice sheets began to melt around 20 ka BP, RSL rose rapidly in what is known as the post-glacial marine transgression. This transgression included the results of a series of rapid “meltwater pulses” at

approximately 14 ka BP (a rise of ~ 3.7 m/100 years), 11 ka BP (~2.5 m/100 years), 9 ka BP, and 8–7.6 ka BP (~1.2 m/100 years) (Figure 1), which affected the rate at which coastal areas were inundated and modified (Woodroffe and Murray-Wallace 2014). Such periods are of interest in terms of how past human occupants interacted with such rapid sea-level change and also how well the archaeological record has survived the changing interaction of the oceanic tide with the continental shelf and coastline.

By the end of the Pleistocene (11.7 ka BP), in most areas, sea level had risen approximately 60 m, and by 7,000 years ago was close to present levels (Figure 1). About 3 percent or 5 million km² of coastal land has been drowned since the Last Glacial Maximum (LGM) (22–20 ka BP). Across the globe, ancient flood stories may relate to post-glacial rising seas or to local sea-level fluctuations over the last thousand years (although many probably relate to more localized failure of ice and landslide dams). More tangible evidence of drowned villages and forests helps define local sea level over the last few millennia and indicates that catastrophic coastal change is an intrinsic part of the earth system. However, at the regional and global scale, the Mid- to Late Holocene experienced relatively little sea-level change compared to the last 150,000 years (Figure 1; see also Woodroffe and Murray-Wallace 2014). It is perhaps within this longer time context that the archaeological record of human migration and coastal and aquatic adaptation should be viewed.

Advancements in archaeological knowledge of sea-level change

Until the late twentieth century, archaeological links with sea level were mainly focused on the emergent records, particularly around the Middle East and Mediterranean. In the early to mid-twentieth century, evidence of lower sea levels and former landscapes was recorded from all sides of the North Sea in the form of submerged forests, Mesolithic-age barbed antlers and carved

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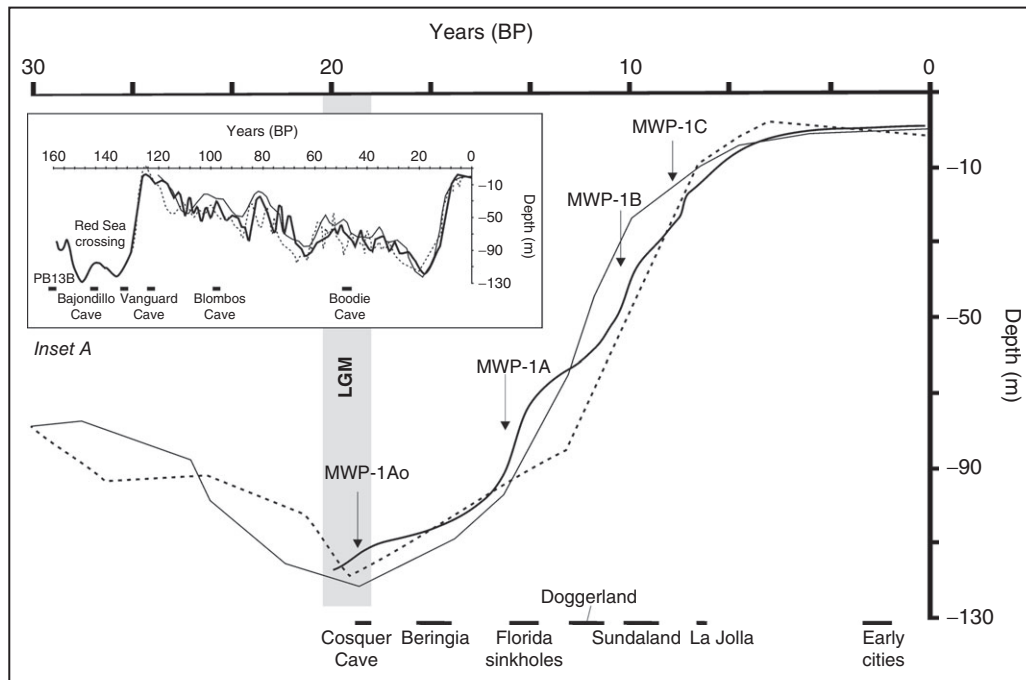


Figure 1 Global (solid lines) and relative (dashed lines) sea-level curves for 160 ka to present, showing the Last Glacial Maximum (LGM) lowstand, major post-glacial meltwater pulses (MWP), and several important archaeological sites associated with lower sea levels (after Bailey 2010).

bones, and in 1957 with the discovery of the first Mesolithic-age submerged settlement, Tybrind Vig, off Denmark (Benjamin et al. 2011). In the Americas, mapping of potential submerged sites for cultural resource management within the Gulf of Mexico has led to a number of discoveries, including most recently an approximately 14,550-year-old megafaunal butchering site in the Aucilla River (Halligan et al. 2016). Along the south coasts of Africa, Spain, France, Italy, and Greece, submerged caves provide clues about early coastal occupation during times of lower sea level, including Blombos Cave, Vanguard Cave, and Cosquer Cave (Figure 1; see also Woodroffe and Murray-Wallace 2014). Ongoing studies in such areas are contributing to debates concerning the emergence of maritime societies, as well as the role of marine food resources in the evolution of the human brain (Bicho, Haws, and Davis 2011).

Until recently, it was thought that marine economies did not develop until the end of the Pleistocene, when the archaeological record begins to show evidence of dietary marine

fauna (see MARINE MOLLUSCS). This view is now challenged, supported by evidence for use of both dietary and utilitarian marine shellfish by early modern humans in Africa (PB13B, Klaises, Blombos Cave), Gibraltar (Gorham's Cave, Vanguard Cave), and the Mediterranean (Bajondillo Cave) from 130 ka BP or earlier, and by anatomically modern humans in South Asia by 42 ka BP (Niah Cave, Lena Hara) and Australia by about 45 ka BP or earlier (Bicho et al. 2011; Veth et al. 2017). Moreover, at several archaeological sites, changes in frequency of different shell species show good accordance with predicted coastal geomorphological and ecological changes, as a response to sea-level changes and an associated change in foraging strategy by humans. There is growing evidence that the intensified use of marine resources and development of associated technologies contributed to the demographic expansion of modern humans into parts of Southeast Asia, Australia, and the Western Pacific about 55–40 ka, the Americas around 13 ka ago,

and later the remote islands of Oceania about 4–1 ka ago (Bicho et al. 2011).

Early in the twentieth century, drowned terrestrial sites were prominent only in theory because the prospection techniques then available could not detect them (i.e., mainly SCUBA). The efficient mapping of such sites has become more important with increasing offshore development, and led to the Danish “fishing site location model” that acknowledged the importance of topography and bathymetry in predicting underwater coastal Mesolithic sites (Benjamin et al. 2011). Since the 1990s, the development and use of remote-sensing instruments, mainly for oil and gas exploration, offer possibilities for locating potential archaeological sites on continental shelves. In many parts of the world, the identification of a number of stillstands (i.e., periods of relatively static sea level) in the post-glacial sea-level curve helped explain the formation and evolution of estuaries, lagoons, barrier islands, coastal dunes, and other sedimentary coastal systems, allowing linkages between the terrestrial and marine record to be made (Woodroffe and Murray-Wallace 2014). These physical features, and any associated archaeological remains, mean that the depth contours obtained from (acoustic) bathymetric surveys can help predictive modeling of the locations of submerged archaeological sites, which is a major theme of current archaeological sea-level research (Harff et al. 2016).

Future directions in research, theory, and methodology

Sea-level research increasingly involves a cross-disciplinary approach involving archaeology, marine geology, marine ecology, molecular genetics, and human biology. Such research acknowledges that high-resolution spatial and temporal data are critical to understanding and preserving the human dimension of changes in sea level. At the same time, interdisciplinary studies of geologic and archaeological archives are providing a better understanding of the magnitudes, rates, and sources of GMSL and RSL rise, and in particular recent and future predicted accelerations of sea-level rise (currently estimated at 3 m/100 years) (Dutton et al. 2015). Estimates of GMSL

and RSL are derived from a range of proxy sources including oxygen-isotopic analyses of ice cores, corals, and coral reefs, mangroves and drowned forests, salt-marsh sediments and microfossils (e.g., foraminifera, testate amoebae, diatoms) (see DIATOMS), shoreline features (e.g., marine terraces, beach and chenier ridges, beachrock), tide-gauge records, and archaeological and historical sites (e.g., ancient ports, wells, ancient fish weirs) (Woodroffe and Murray-Wallace 2014). Of these, salt-marsh sediments, coral, and archaeological indicators provide the best means of correlating paleo-sea-level and historical data.

While records of local and relative sea-level change are obviously important to archaeology, sea-level data alone are often not sufficient for past and future archaeological reconstructions because it is not necessarily the magnitude of sea-level change that is critical but rather how it fluctuates. These fluctuations, and their precise nature—that is, whether linear or episodic—help determine the character of coastal and nearshore environments that people used, and potentially the timing of colonization (Bailey and Parkington 1988; Bicho et al. 2011). Such ideas contribute to changing perspectives on the habitats and resources used by hunter-gatherers during different phases of sea-level change, to the importance of changing marine ecosystems in human evolution, and, in turn, to the consequent impacts of humans on nearshore ecosystems (Harff et al. 2016). At the same time, a better understanding of human demographics and adaptation to past changes in sea level and coastal geographic change can inform our response to current and future sea-level change, including, for example, consideration of the vulnerability of coastal archaeological sites (Erlandson 2012). Hence, it remains important to continue to refine knowledge of patterns of past sea-level change.

SEE ALSO: Environment and Landscape; Environmental Archaeology

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Sheep and Goats

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Sheep and goats (ovicaprids) have been hunted or husbanded for food (e.g., meat, milk, and marrow), fibers, carcass by-products (e.g., fats, hides, horn, gut, and sinew), and dung. Sheep have been the subject of intense breeding for wool, while goats produce more milk and young and can fare well in poor environments. Both animals have been used as flock leaders, as pack animals, and for light traction. They also held and continue to hold important symbolic roles in many societies and religious faiths. The relative frequency of ovicaprids and the ratio of sheep to goats in archaeological sites can vary widely by area, period, and cultural and socioeconomic context.

Taxonomy and biology

Sheep and goats (Order Artiodactyla; family Bovidae; subfamily Caprinae) are similar in size and shape, but with key biological differences, including type and location of scent glands, coats, and horn shape. Wild sheep species include the mouflon, urial, argali, and snow sheep found in Asia and northeast Siberia, and the bighorn and Dalls sheep of North America. There are numerous wild goat species (tur, markhor, ibex, bezoar) found across Eurasia and in northeast Africa. Domestic sheep (*Ovis aries*) and goats (*Capra hircus*) are found worldwide, with genetics confirming that each descends from a single wild progenitor species, the Asiatic mouflon (*Ovis orientalis*) and bezoar (*Capra aegagrus*), respectively (e.g., Davis and Simões 2016).

Both genera are herbivores. Sheep are grazers, feeding on grassland vegetation, while goats browse on trees and shrubs, though both vary their diets depending on geographical location and season. Wild sheep are generally found in hilly regions and foothills, while goats prefer

steep, mountainous, and rocky terrain. They may move daily or seasonally to drink and feed. Marked seasonal weight loss may occur, including in domestic hill flocks (Worley et al. 2016).

Wild sheep and goats are gregarious, forming small cohorts of under 30 animals depending on sex, age, and breeding season, and occasionally congregating in larger herds. This characteristic would have assisted their domestication. In temperate zones, mating occurs mainly in the fall (when day-length decreases and the hormone melatonin increases), while in the tropics, where day-length varies little, reproduction occurs year-round. The gestation period in both species is about five months, though this, and fecundity, vary with breed and nutrition.

Methods of zooarchaeological study

Sheep and goats are mainly studied through osteology, with reliability in species identification depending on skeletal element, intraspecific variation, age at death, and geographical origin. Often bones can only be categorized as ovicaprid. Since the 1960s, many morphological and metric criteria have been developed to improve determination, with recent work focusing on examining reliability or expanding their application and interpretive potential (e.g., Davis and Simões 2016).

Population reconstruction based on age at death (from bone fusion, and tooth eruption and wear) may suggest a focus on particular products and forms of management, though mixed-husbandry systems are often the norm (Vigne and Helmer 2007). Bone fusion occurs in a consistent sequence, but happens earlier in females and is delayed in castrates (Popkin et al. 2012). Timing of dental eruption shows much less variation between sexes and this offset holds potential for characterizing management. Tooth wear can be particularly variable in older animals, influencing the reliability of derived mandible stages (Worley et al. 2016). Species and sex distinction greatly enhance interpretation of age profiles (Mainland 2006; Vigne and Helmer 2007).

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In wild animals, the bones of males are considerably larger than those of females, but in domesticates this differential is reduced and sex distinction is complicated by castration, which leads to longer and more slender limb bones. Sex distinction can also be obscured by metric variation between populations (e.g., breeds), so population “uniformity” needs to be assessed to make valid interpretations (Popkin et al. 2012). Where sufficiently intact, horncore or pelvis shape may be diagnostic of sex.

Bone size and shape can inform on domestication and husbandry, breed development, health, and physiological demands (pregnancy, lactation). The log-ratio method—comparison with measurements of a “standard” individual or population average—is a common analytical approach. Multivariate statistics have been used to confirm metric criteria (e.g., Popkin et al. 2012).

Domestication and diversification

Domestication (see DOMESTICATION) of sheep and goats probably occurred on many independent occasions in the Northern Fertile Crescent, in the mid-ninth millennium BCE (Davis and Simões 2016). Diversification would have followed rapidly as animals were moved, adapted to new environments, and were selected for specific traits. Numerous, probably regional varieties of sheep are described by classical authors, and zooarchaeological data have contributed to debates regarding timing of these and later livestock “improvements” (Davis 2008).

Early domesticates were similar in size and shape to their wild counterparts. Horns were among the first traits to change, for example from the long and scimitar form in wild male goats to a twisted, helical shape in domesticated animals. Hornless individuals are rare in mouflon and all goats, but evident in Chalcolithic images of domestic ewes. Some breeds have multiple horns. Other skeletal changes include reduction in limb bone length and lengthening of the tail. Analysis of astragalus measurements indicates greater bone robustness and shape variation in sheep, which may reflect more intensive selective breeding for wool and meat, compared to goats (Davis and Simões 2016).

Wild goats and sheep both have coarse hairy outer coats (kemps) and softer insulating undercoats. In sheep, the naturally molting short fibers of the undercoat have been developed through selective breeding into fleeces of varying length and quality; in primitive breeds, wool may be hairy and is plucked rather than shorn. Domestic goats have remained primarily hairy, but a few breeds produce substantial fine-quality fleeces, for example Angora and Cashmere. Early domesticates were probably dark/tan colored, as are wild animals and primitive breeds such as the Soay. Wool colors, from pale tan through to gray and black, have been identified in Bronze Age textiles, with a “new” nearly white type evident at Middle Bronze Hallstatt (Rast-Eicher 2014, 194).

Use

Sheep and goats may be raised for consumption at a young or “prime meat” age, or consumed following use for breeding, dairying, or wool production. In some societies, ovicaprid meat was preferred over that of other species. For example, the size of sheep increased during Islamic rule in Portugal, which along with younger slaughter (compared to earlier or later periods) suggests that sheep were bred to provide a greater amount of mutton and lamb, much appreciated in Arab cuisine (Davis 2008).

Ovicaprid milk can be used to produce cheese, yoghurt, and butter, with productivity varying between species, breeds, and environments. Dairy production (see DAIRYING) may be indicated by high representation of adult females, and surplus young killed to free-up milk supply, and through residue analysis (see ORGANIC RESIDUE ANALYSIS). In early Neolithic sites in France, goats may have been kept for milk, while sheep show a more mixed use (Vigne and Helmer 2007).

Goat hair and sheep’s wool are used for clothing, containers, and textiles (see TEXTILES). The wool industry was a key driver of the European medieval economy, evident in the high ratios of sheep (and ovicaprids) in bone assemblages. Historic records indicate that large numbers of males were castrated in order to improve the quality (finer, less greasy) and volume of fleeces, but their identification remains a key challenge

in zooarchaeology (Davis 2008; Popkin et al. 2012).

Bones in cremations and temples or shrines may show a concentration on a single species, restricted age groups, and body parts. Deposits of sheep and goat astragali can include hundreds of bones, their abundance and frequent modification suggesting ritual and secular (e.g., gaming) uses.

Management

Ovicaprids are managed in a variety of ways including nomadic, semi-nomadic, and transhumance pastoral systems, and in some cases supplementary foddering. Pasturing of sheep and goats on crop stubble and fallow land to improve soil fertility has long been an important seasonal activity for transhumant herders and agropastoralists.

Tooth microwear and biomolecular methods (see ZOOARCHAEOLOGY AND ANCIENT DNA and ZOOARCHAEOLOGY AND STABLE ISOTOPES) can inform on livestock management. Microwear analysis shows that grazing, browsing, and foddering of sheep and goats leave characteristic traces on tooth enamel, reflecting abrasion by food and soil ingested prior to death (Mainland 2006). At Neolithic Catal Hoyuk (Turkey), microwear and oxygen isotope analysis suggest that herds were pastured year-round near the settlement, using an outfield system including river valleys, and births were scheduled to coincide with optimal food availability in late spring. Farmers attempted unsuccessfully to vary birth season to early spring, while herd diet gradually shifted to clean, drier, grassy food, possibly through the use of more distant pastures or changes in foddering (Henton 2012).

Various pathologies may be linked to animal management. Horncore depressions and thinning of bone in ewes may reflect physiological stress during pregnancy and lactation. Osteophytes on the elbow joint and metapodials have been linked to penning, crowding, use of crooks, and uneven terrain. Overgrazing and ingestion of soil and harmful weeds may result in oral injury, such as alveolar recession, infection, and tooth loss.

New and future directions

Genetic analysis can allow secure distinction between species and continues to be instrumental in exploring domestication. Zooarchaeology by mass spectrometry (ZooMS) is based on a method of collagen peptide sequencing. It can also distinguish between wild and domestic sheep and goat species using very small samples and has been highly successful in the study of ancient parchments (Fiddymment et al. 2015). Baseline research in biochemical markers, including isotopes, is a priority for reliable interpretation of diet, mobility, and trade. Computer modeling has recently been used to investigate the role of domestication in disease transmission among humans and goats.

SEE ALSO: Food Residue Analysis; Geoarchaeology; Paleopathology; Taphonomy; Zooarchaeology

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Sorghum and Pearl Millet

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Sorghum and pearl millet are widespread and important cereals in indigenous African agriculture (Harlan 1992), and they are also widely cultivated in India, mostly in the hot dry plains of southern and western India (Figure 1). Both are tall, thick-stalked cereals, often growing to 2 m or more in height. Both also are grasses with the C_4 photosynthesis, and as such are drought tolerant and well adapted to semi-arid savannah environments.

Pearl millet is arguably the most arid-adapted crop in the world, being grown along the southern margins of the Sahara, and reaching maturity sometimes on just 250 mm of rainfall, producing a crop within as little as three months (Brunken, de Wet, and Harlan 1977; Neumann et al. 2012). Various varieties or races of pearl millet are distinguished by how quickly they mature, the amount of tillering and branching, the size, shape, and compactness of the inflorescence, as well as the grain size, color, and shape.

Sorghum can be grown with as little as 300 mm of rainfall, but is considered most productive in areas with 500–800 mm of annual precipitation. As with pearl millet, many distinct varieties exist, differentiated particularly by their panicle shape and density, along with the size and shape of the grain, and the length and character of the glumes surrounding them. For sorghum these races often relate to the ecological zones in which they are found, with races such as *guinea* with large open loose panicles being associated with the rainforest zone, while is more commonly cultivated within drier habitats. Differentiation and dispersal in Asia has also included the evolution of Chinese Kaoliang sorghums, with tight-fitting hulls but having genetic similarities to free-threshing forms recorded in India. Kaoliang sorghum extends to temperate conditions in northeast China, Korea, and Japan to nearly 40 degrees latitude.

Regarding the wild ancestors of pearl millet and sorghum, the situation has been greatly complicated by the complex history of taxonomy that has existed for both species. In particular, the likelihood of a great many introgressions having occurred between wild and domesticated populations as both crops spread throughout the African and later Asian continent over the past 5,000 years has further added to this problem. The wild ancestor of sorghum using the binomial system is *Sorghum verticilliflorum* (Steud.) Stapf. or *Sorghum arundinaceum* (Desv.) Stapf (and using the binomial system syn. *Sorghum bicolor* subsp. *verticilliflorum* (Steud.) de Wet ex Wiersema & J. Dahlb.). Genetic work strongly suggests that modern cultivars are most strongly aligned with wild sorghum populations within central and northeast Africa (Fuller and Stevens 2018). The wild ancestor of pearl millet is attributed to *Pennisetum violaceum* (Lam.) Rich, although many papers refer to *Pennisetum glaucum* ssp. *monodil* (following syn. *Pennisetum americanum* subsp. *monodii* (Maire) Brunken). The likely origin of the wild progenitor lies within the Sahelian regions of West Africa.

Archaeological evidence indicates that sorghum was widely gathered as a wild food resource during the Early and Middle Holocene in the central and eastern Sahara under wetter conditions associated with the African Humid Period (ca. 14,800–5,500 years ago). These earliest finds of gathered wild sorghum include specimens from Egypt, Sudan, and Libya (Fuller and Stevens 2018). In terms of evidence for domestication (see DOMESTICATION), the earliest evidence for morphological change brought about by human cultivation is from chaff remains in ceramics from the eastern Sudan (near the Atbara River) between 3500 and 3000 BCE, associated with predominately forager-pastoralists who still had a strong reliance on hunting. After this, the archaeobotanical record (see PALEOETHNOBOTANY) in Africa is sparse, but sorghum had reached the Niger River basin by the mid- to first millennium BCE (Fuller and Stevens 2018). Sorghum was presumably an important crop

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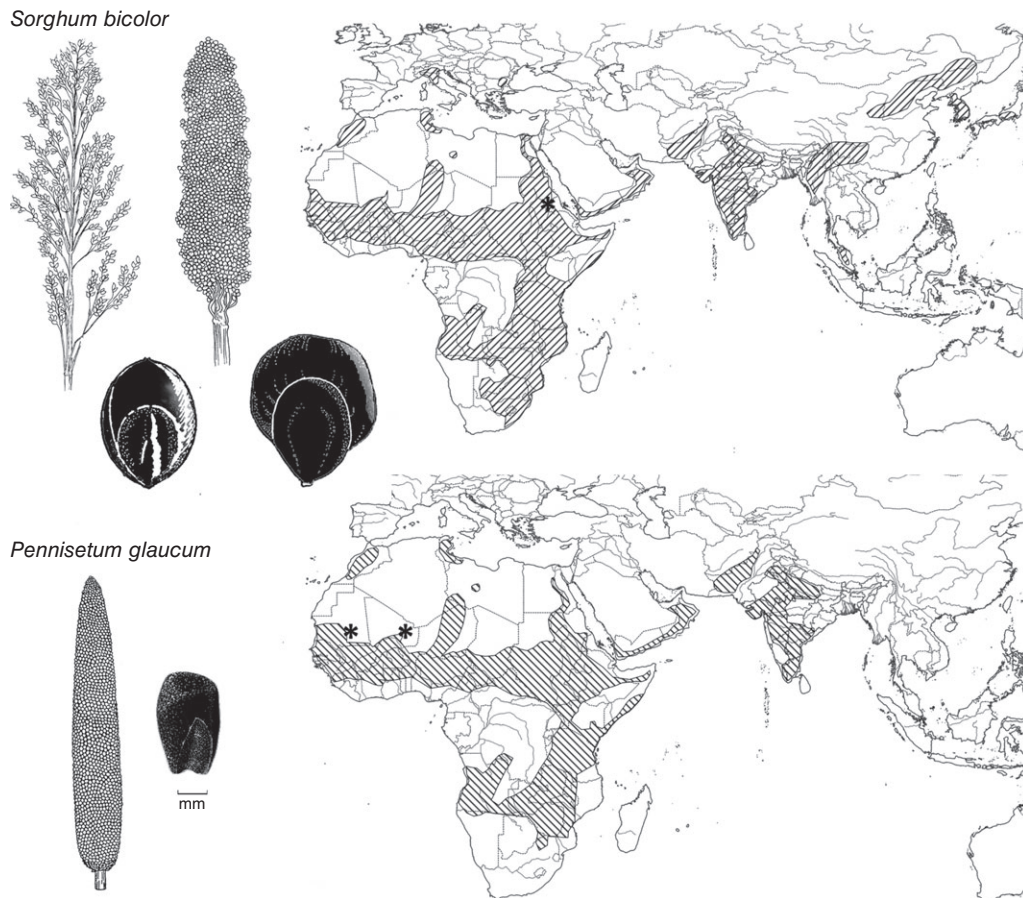


Figure 1 Distribution of traditional/pre-colonial areas of cultivation (hatched) for sorghum (*Sorghum bicolor* (L.) Moench.) (above) and pearl millet (*Pennisetum glaucum* (L.) R. Br.) (below). Sites with the earliest finds of domesticated types are denoted by asterisk.

prior to this in the savannas, and had become established as a major cereal in the Nubian Nile valley within the final centuries of the first millennium BCE, during the Meroitic Kingdom, where it is associated with irrigated summer cultivation that alternated with winter cultivation of cereals like wheat or barley (Fuller 2014).

Pearl millet (bulrush millet) has been found occasionally as a wild food among central Saharan foragers of the Early Holocene, but emerged as a crop along the southern Saharan fringes of western Africa. The earliest evidence for domesticated types comes from northeastern Mali dating to around ca. 2500 BCE. Finds to the west from Mauritania dating from the early second millennium BCE may represent a separate domestication process, while finds between 2000 and 1500 BCE

in central Mali, Ghana, and Cameroon attest to the spread of pearl millets throughout the western Savannas (Zach and Klee 2003; Manning and Fuller 2014). Around 400 BCE, pearl millet has been found on sites located today within the damp tropical rainforest areas of southern Cameroon, in wet environments where the crop cannot be grown today. This was made possible by a climatic shift dating to around 2,500 years ago, in which winter dry seasons became more pronounced in central Africa, leading to the establishment of more savannah elements in the rainforest zone (Neumann et al. 2012).

In eastern Africa, the spread of pearl millet is strongly tied to the spread of sorghum, and both have been linked to groups speaking Eastern Bantu and Nilo-Saharan (Central Sudanic and

Nilotic) languages. These are the earliest cereals of crop cultivation known in eastern Africa, although pastoralism without crop cultivation may be as much as 3,000 years earlier. Early finds near the African Great Lakes are from the first centuries CE, while on the east African coast (coastal Kenyan) and nearby Tanzanian islands these cereals were cultivated by 600 CE (Crowther et al. 2016). Shortly thereafter, both of these cereals reached southern Africa associated with the spread of Iron Age agropastoralism.

Despite the apparently late spread of sorghum and millet agriculture throughout much of sub-Saharan Africa, both these crops have been shown to have reached tropical Asia shortly after domestication. Pearl millet and sorghum, as well as some evidence of Africa beans, are present on archaeological sites in Gujarat, India by ca. 1700 BCE, and they are found in the Ganges plains and in southern India by around 1500–1000 BCE (Fuller 2003). Such evidence indicates an early translocation of African crops to tropical savannah environments of India via maritime contacts, most likely around the Arabian Peninsula, at a very early date, the process for which was been a recurrent issue of discussion and debate among archaeologists.

The evolution of varietal differentiation, which taxonomists identify as races, is of some interest in tracing the movement of both these crops. These races are partly geographical, but also reflect both conscious and unconscious selection for different physiological characteristics, particularly with regard to the nature of the inflorescence and grain. In the wild form and among the more primitive cultivars, grains are tightly clasped in husks, and hence require dehusking after the spikelets have been threshed to release the grain. But in both species, free-threshing varieties have evolved in which the grains are no longer fully enclosed within the husk and protrude from the spikelet, hence no longer requiring dehusking. In sorghum, free-threshing varieties evolved at least three times in different geographical races, referred to as *durra*, *guinea*, and *caudatum* (Harlan 1992; Fuller and Stevens 2018). In pearl millet, hulled forms are grouped within the widespread primitive race *typhoideum*, whereas other forms are all free-threshing (Brunken et al. 1977). While all pearl millet inflorescences are dense and compact, facilitating harvest, sorghum races have

evolved after domestication from loose panicles to much denser, compact inflorescences. Among the densest, tightest panicles, with free-threshing grains, is the sorghum race *durra*, thought to have evolved early in India and then dispersed back to Yemen and northeast Africa (Sudan) around 2,000 years ago.

Today, sorghum is consumed in a great many ways, including as gruel, beer, stiff porridge, and flat breads, while certain varieties can be toasted in a similar fashion to popcorn. In China, following traditions of sticky rice and millets, sticky forms of sorghum have been bred and used in a similar manner within local cuisines. While sweet-stemmed varieties of sorghum, *Sorgos*, have a long ancestry in Africa and India where they are used for fodder, they have been bred during the nineteenth century within the United States for production as a sweet sorghum syrup.

Pearl millet has similar uses to sorghum, being prepared as gruels, porridges, flat breads, and beer. However, it is worth noting that the germ or embryo ratio to grain in pearl millet is much higher than within many other cereals, and as such it yields relatively less flour with grinding. However, the heads of pearl millet can also be steamed and/or roasted and consumed in a similar manner to corn-on-the-cob or sweet-corn.

SEE ALSO: Barley, Rye, and Oats; Beverages; Maize; Rice; Wheat

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Spices

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Spices improve the taste of our dishes but also have properties that promote human health. As will be shown in this entry, the use of spices in human nutrition has a long tradition stretching over many thousands of years. Although spices were not used extensively during the last hundred years, at least in the western world, thanks to the modern globally inspired kitchen they have experienced a comeback. While salt (sodium chloride) might be considered a spice by some, it is an inorganic substance rather than of plant origin and therefore outside the scope of this entry. When thinking of spices, many of us think of pepper (*Piper nigrum*), chili (*Capiscum annum*), cinnamon (*Cinnamomum verum*), and cloves (*Syzygium aromaticum*): in other words, with something having an exotic taste! Not many of us consider that herbs like marjoram (*Origanum majorana*), thyme (*Thymus vulgaris*), and dill (*Anethum graveolens*) also fall under this category. Seeds such as those of pepper, whole fruits such as chili pods, tree bark such as cinnamon, and leaves such as bay (*Lauris nobilis*) are used to flavor our daily meals. It is not only the taste but also the effect on our digestion system, our blood pressure, and our heart activity that make the spices worth a closer look. Spices can be used as aphrodisiacs and as preservatives to help keep food free of bacteria and mold, and, last but not least, many spices are used for their particular type of fragrance, processed into perfumes or burnt to produce aromatic smoke.

Applying archaeobotanical methods, it is possible to obtain evidence for the long-term use of spices. The most common procedure is to take soil samples during the excavation and analyze them in the laboratory by washing the sample with water using sieves with mesh sizes down to 0.2 mm. The residues in the sieves are then screened under a binocular microscope, and the selected

plant macroremains such as seeds, fruits, leaves, and threshing remains are then determined by comparison with modern botanical reference collections (see PALEOETHNOBOTANY). Food residues in ceramics and equivalent containers are studied by applying microscopic methods in order to detect visible plant microremains, such as starch grains (see STARCH GRANULE ANALYSIS) and phytoliths (see PHYTOLITH ANALYSIS). By applying chemical methods, as, for example, mass spectroscopy or newly developed analytics in biomolecular science, the main components of food and drink such as lipids or fatty acids can be traced (see ORGANIC RESIDUE ANALYSIS).

Recent archaeobotanical finds of chili pepper in the New World indicate that this is one of the oldest spices, with evidence of cultivation 6,000 years ago. This is based on phytolith records of chili from seven excavated sites, both in the Amazon basin and on the coast of Ecuador (Perry 2015). Since Columbus discovered America, chili has spread around the whole globe and plays an important role in both the Asiatic and eastern European kitchen.

Exotic spices such as pepper, cardamom (*Elettaria cardamomum*), cinnamon, and nutmeg (*Myristica fragrans*) have their origins in the subtropical and tropical regions of Southeast Asia. The beginnings of their cultivation are still not properly explored, although it has been established that spices were traded from these regions to Egypt from at least the second millennium BCE (Cappers 2006; Van der Veen 2011). Even the transport of living spice plants is shown on the reliefs that are depicted at the walls of the temple of Deir al-Bahri which is situated close to Egypt's Valley of the Kings. This is the grave monument of the female pharaoh Hatshepsut who ordered the transport of living myrrh trees from Punt to Upper Egypt around 1495 BCE. Punt was most probably located in northern Somalia. Written sources also exist from this time period describing the medical properties of spices. The most famous is the transcribed Papyrus Ebers. These sources prove that people knew about the antibiotic properties of garlic, for example, even by this early date.

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Direct evidence for the consumption of wild collected garlic (*Allium* spp.) is available in the form of pollen (see PALYNOLOGY) recovered from 6,000-year-old human feces (see COPROLITES) that were found in several of the UNESCO lake dwelling sites in the circum-alpine region of central Europe. Wild garlic was clearly collected and frequently consumed by these early farming communities. A belief in the potency of wild garlic is suggested by the numerous finds of cloves, especially in women's graves dated to the first millennium CE that have been excavated in northern Europe (Karg et al. 2014).

During the first millennium BCE, herbal medicine flourished in Greece. The most famous book from this time is the *Corpus Hippocraticum* written by Hippocrates who lived between 460 and 370 BCE. He describes 230 different medicinal plants. Some years later, the father of botany, Theophrastus (ca. 371–287 BCE), wrote ten books concerning the *Enquiry into Plants*, of which nine have survived. Spices from Asia such as cinnamon and cardamom are described in these books (<https://en.wikipedia.org/wiki/Theophrastus>). Spices and herbs were also so much appreciated in ancient Rome that they were used as valuables and a means of payment: for example, pepper. The Roman legions introduced some of the spices to central and western Europe (Orengo and Livarda 2016), while along the Silk Road, which was the trading route from China to Europe for many centuries, spices were exchanged with other goods such as silk, silver, and fur. Via this route many spices were transported to Europe during the first millennium CE.

Archaeological spices can best be recovered from storage facilities or latrines in which human excrements are often mixed with kitchen refuse. Latrines were normally dug deep into the ground and the archaeological layers that built up in them are therefore preserved under anaerobic conditions that exist below the permanent modern water level, meaning that organic material is perfectly preserved for thousands of years. Depending on the local climatic circumstances, plant remains can also be preserved through desiccation, for example in desert regions. In wetter climates, the chances of finding plant remains preserved through desiccation is much reduced and only occurs in special circumstances, such as within coffins or closed metal

containers (Karg et al. 2014). Charred records of spices are generally few and far between, except for excavations of kitchens or storage areas.

Besides archaeobotanical finds dated to the first millennium CE, written documents describe the cultivation of useful plants. The best-known sources for central Europe are:

- the *Capitulare de Villis* (ca. 800 CE);
- the monastery plan of St. Gallen (ca. 820 CE);
- the *Hortulus Walahfried Strabo* (ca. 830 CE).

In the *Capitulare de Villis*, 89 vegetables, fruit trees, and spices that should be planted in enclosed gardens are listed (Strank and Meurers-Balke 2008). Spices that are both recorded in the form of archaeobotanical finds in northern Europe and named in the *Capitulare de Villis* are published in Karg (2014) (Table 1). Precise information about the use of herbs for medicinal purposes is described in the writings of Hildegard from Bingen who lived during the twelfth century in central Europe. Throughout the Crusades during the thirteenth century, knowledge about spices was spread widely. The ancient trading centers in northern Egypt (Cairo and Alexandria) were superseded by Venice, Genoa, and Pisa. These towns became very prosperous during the medieval period due to the cleverness of the spice traders. It is said that one pound of saffron (*Crocus sativus*) had the same value as one horse, one pound of ginger (*Zingiber officinale*) was equal to one sheep, and pepper was compensated with gold.

The riches that could be gained by trading with spices triggered the voyages of discovery. When Vasco da Gama returned from India in 1499 with ships loaded full of spices, the Italian dominance was set to end. Now, it was Portugal that declared the prices for spices. A cinnamon monopoly guaranteed high profits which were used for financing more voyages. It was with the discovery of the New World that new spices such as allspice (*Pimenta dioica*), vanilla (*Vanilla planifolia*), and paprika and chili (different forms of *Capsicum annuum*) were introduced to Europe. In Spain, the cultivation of paprika occurred rapidly following its introduction and spread from there.

The spice trade was also a highly political affair. This is seen by the fact that in 1602 the Dutch founded the first public limited company of the world, the Dutch East Indian Company, which held the monopoly in the trade of nutmeg and cloves.

The global spice market, which started with the discovery of the Americas some 550 years ago, can be seen as one of the triggers for European expansion. Shipbuilding yards and warehouses boomed, exotic dishes were promoted in new cookery books, and new food traditions developed. Set against the profit of the western world, it is a tragic history of the numerous colonies, battles and wars, exploitation of local people, and destruction of natural environments. The end of World War II meant the end of the spice monopolies. However, today many spices still play an important socioeconomic role in their countries of origin. The story of how, where, and why the know-how of intensive spice production began and developed should receive much more attention in the future before it falls into oblivion.

SEE ALSO: Beverages; Fruits, Vegetables, and Nuts; Urban Environments

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Starch Granule Analysis

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Starch granule analysis is a microbotanical technique used by archaeologists to document past uses of plants by humans. Starch granules are composed of carbohydrates and are produced by plants as an energy reserve. They are found in large quantities in many of the plants consumed by humans as food, including underground storage organs (roots and tubers) such as potato, yam, and cassava; grains such as wheat, rice, and maize; fruits such as banana and breadfruit; and various nuts (Figure 1). Variations in the size and shape of starch granules between plants can enable the identification of specific botanical taxa. In some cases, plants, where other remains, such as seeds, phytoliths (see PHYTOLITH ANALYSIS), or pollen, are undiagnostic or do not preserve well, produce starch, making this technique an important addition to the paleoethnobotanical toolkit (see PALEOETHNOBOTANY), particularly in tropical regions where subsistence typically relies on vegetative rather than grain crops. Starch granules can be found archaeologically as residues on the surfaces of stone tools, pots, and other food-processing implements, in sediments from agricultural features or activity areas, or trapped in dental calculus, coprolites (see COPROLITES), stomach contents, and charred or desiccated food remains. As such, starch granule analysis can provide complementary and unique paleoethnobotanical insights into many aspects of past human behavior, including diet, plant-processing activities and their on-site spatial arrangements, artifact function, early agriculture, and crop dispersal histories. The study of ancient starch granules generally requires chemical extraction from the source material and the use of a light microscope for identification (see OPTICAL MICROSCOPY) (Torrence and Barton 2006).

Starch granules are mainly composed of two polysaccharides, amylose and amylopectin, as

well as minor quantities of lipids and proteins. Amylose (which has a linear structure) and amylopectin (which is highly branched) are arranged within the granule in regular, alternating amorphous and crystalline layers, which accumulate concentrically around a growth initiation point known as the hilum. The high degree of molecular and crystalline order within the granule gives starch granules semicrystalline properties. As such, granules display birefringence and form a Maltese-shaped extinction cross through the hilum when viewed with a cross-polarized light microscope (Figure 1b, d, and f). These features provide the main optical properties used to recognize starch granules. Storage starch granules form in specialized plastids called amyloplasts, where they can occur either as single “simple” granules up to 200 μm in size when mature, or as compound aggregates. Starch is also produced in chloroplasts within stems, leaves, and other photosynthetic tissues; unlike storage starch, such starch is synthesized on a daily basis and usually small ($<5 \mu\text{m}$) and morphologically nondiagnostic (Haslam 2004).

The attributes recorded to differentiate and identify starch granules include size, overall shape in both two- and three-dimensions (e.g., round/spherical, ovoid/ovate, polygonal/polyhedral), and variations in the granule outline, position of the hilum, distortions of the cross, the presence or absence of surface facets, internal fissures, and growth rings, and whether or not compound granules are present (Torrence and Barton 2006; see the International Code for Starch Nomenclature (ICSN 2011) for standardized morphological descriptors). Starch granule identification usually relies on direct comparisons between these features in archaeological and reference assemblages constructed from local plant flora in the study region. Multivariate methods have been explored as a more objective means of starch identification (e.g., Coster and Field 2015).

One of the more contentious aspects of ancient starch concerns preservation, with mechanisms contributing to long-term survival and diagenesis (see DIAGENESIS OF BONE and TAPHONOMY) still

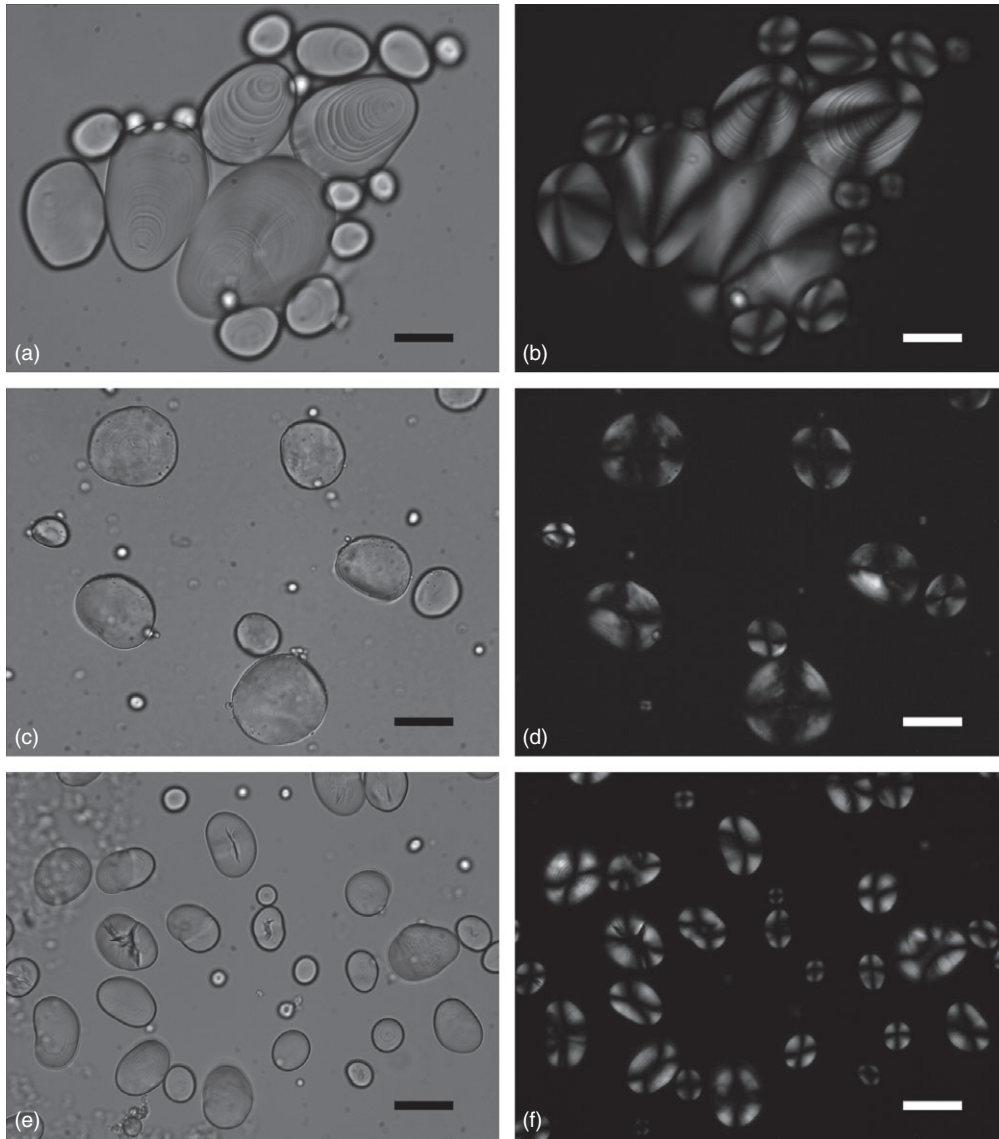


Figure 1 Images of starch granules from common food crops. (a, b) Potato (*Solanum tuberosum*, tuber). (c, d) Bread wheat (*Triticum aestivum*, seed). (e, f) Lentil (*Lens culinaris*, seed). (Scale bars are 20 μm; b, d, and f are in cross-polarized light).

not fully understood. Archaeological studies demonstrate that granules can survive long periods (at least 200,000 years in mineralized calculus deposits) (Henry, Brooks, and Piperno 2011) in a range of depositional settings, despite their susceptibility to degradation by various physical, biological, chemical, and thermal processes. These processes include enzymatic hydrolysis by soil-borne microorganisms, mechanical attrition

by movement or compaction of the depositional sediment, stress fracturing from freezing or repeated cycles of wetting and drying, chemical dissolution caused by very acidic or alkaline conditions, and thermal decomposition caused by exposure to extremely high dry heat (>180 °C), or moderate heat (>40–50 °C) in the presence of moisture (Haslam 2004). These processes can affect starch survival prior to deposition

in the archaeological record such as during plant processing, as well as after deposition. The susceptibility of starch to degradation varies within and between plants depending on the granule's intrinsic species-specific properties (e.g., shape, size, composition), which creates many challenges for archaeologists attempting to reconstruct past assemblages from surviving altered compositions.

The main survival mechanism cited by archaeologists draws on the observation that starch granules appear to preserve best in protected microenvironments, such as embedded in pits and cracks on artifact surfaces, or encapsulated in mineralized dental calculus, charred residues on pottery, or soil aggregates. Desiccating or anaerobic environments and the presence of certain microbe-inhibiting compounds such as metals (e.g., copper, manganese) and tannic acids in the depositional environment may promote starch survival (Haslam 2004). Starch burial experiments have generally supported these observations, but have highlighted the highly variable nature of decay depending on local depositional conditions. Decay rates have been shown to slow down over long depositional periods, particularly in stable burial environments in which starch granules and their degrading mechanisms are more likely to reach equilibrium.

Food processing can modify, and in some cases completely destroy, starch, affecting its deposition and survival in the archaeological record. Activities such as cooking, grinding, and fermenting, which are often essential for transforming starch-rich plants into an edible form or for preparing particular ingredients such as flours, can impart characteristic alterations to the morphology of starch granules (Babot 2003). Importantly, however, these degradation patterns can help archaeologists identify such culinary behaviors in the past. For example, starches recovered from grindstones or pounding tools often display modifications such as cracking, tearing, and breakage, as well as roughened surface textures caused by mechanical processing. During fermentation, starch-specific enzymes called amylases break down the granule's concentric growth layers, sometimes leaving characteristic corrosion channels, as observed on starches in ancient beer-brewing residues. The most extreme

alterations to starch granules occur during cooking, which can cause granules to swell, lose their structure and birefringence, and eventually disintegrate. Intact cooked starch granules can nonetheless still be recovered from food residues on pottery and dental calculus, though their taxonomic identification is usually restricted owing to the loss of gross morphology.

Analyses of starch residues preserved on the used surfaces of archaeological stone tools and ceramics have drawn on these characteristic alteration patterns to provide complementary information about the functions of food-processing technologies. In some cases, these studies have demonstrated uses different to those recorded in ethnographic sources. The frequency and distribution of starch granules on different surfaces of the artifact, the presence of other plant microresidues such as phytoliths, and analyses of associated use-wear patterns are commonly used to support such functional interpretations. Associated sediment samples as well as laboratory consumables should be analyzed routinely for background starch to rule out post-depositional contamination of the artifacts (e.g., Nadel et al. 2012; Crowther et al. 2014).

Starch residues on tools used in food preparation or in sediments from such activity areas can give indirect clues about the role of plants in human diet. However, more direct dietary information can be gained by analyzing starches preserved in charred or desiccated food remains, dental calculus, stomach contents, coprolites, and cess pits. Dental calculus in particular has become a key source of evidence of early diet, including that of our hominin ancestors, owing to the long-term preservation potential of its mineralized composition (Henry et al. 2011). Another advantage of using this approach to reconstruct diet is that plant foods that can be eaten unprocessed (such as certain starchy fruits and nuts), and are therefore unlikely to leave traces on artifacts, may be detected in calculus or paleofecal remains. However, it is presently unclear how representative these remains are of past diet, owing to a variety of short- and long-term temporal biases and a still-poor understanding of the accumulation processes involved in the formation of calculus. Coprolites only reflect foods consumed in a short time prior to excretion by a single individual, whereas cess

deposits can reflect much longer time periods relating to multiple individuals. Starch granules recovered from food storage contexts (such as sediments from storage areas, pits, or bins, or in residues on storage vessels), and food discard (such as midden or refuse pits) may indicate the types of foods available for consumption. Evidence of plants used for medicinal and other nonfood purposes can be recovered from calculus and paleofecal sources.

Another area of study in which starch granule analysis has helped make significant advances is the origins and spread of agriculture. Starch granules have provided some of the earliest evidence for cultivated crops in tropical regions such as the New World Neotropics, Southeast Asia, and the Pacific, where many early crops are vegetative and often do not preserve well or produce other diagnostic remains. Studies are expanding in more temperate regions such as east and southwest Asia. Detailed reference collection analyses have focused on differentiating the starches of domesticated crops from those of their wild relatives based on subtle differences in the size and shape of the granules within a population. One of the best-studied examples is maize (*Zea mays*) (Holst, Moreno, and Piperno 2007) (see MAIZE). Another source of evidence for early agriculture comes from starch granules in sediments from agricultural features or on associated artifacts. Aspects of the production systems involved may be inferred based on landscape transformations and the agronomic requirements of the plants, as demonstrated at Kuk Swamp in the Papua New Guinea highlands (Denham et al. 2003), particularly in conjunction with ethnographic studies of traditional practices in the study region.

Despite being a relatively novel paleoethnobotanical method, starch granule analysis is rapidly growing in the scope of materials, time periods, and regions around the world to which it is being applied. The ongoing development of regionally specific reference collections and starch identification keys for economic taxa will continue to facilitate this expansion and provide new insights into past plant use, including in deep-time settings. Another aspect of starch granule analysis that is likely to see significant advances in future concerns molecular taphonomy. A better understanding of factors affecting the long-term preservation and diagenesis of

starch may resolve debates about the reliability of archaeological identifications and interpretations. More rigorous understanding of these issues, particularly through biomolecular studies, will ensure robust reconstructions of past relationships between people, plants, and the environment using this technique.

SEE ALSO: Coprolites; Diagenesis of Bone; Domestication; Environmental Archaeology; Food Residue Analysis; Fruits, Vegetables, and Nuts; Maize; Optical Microscopy; Organic Residue Analysis; Paleoethnobotany; Phytolith Analysis; Taphonomy

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Taphonomy

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The term taphonomy (from the Greek words *taphos* meaning “burial” and *nomos* meaning “laws”) was originally selected by Russian scientist Ivan A. Efremov (1940) to name a specialization within paleontological research devoted to the *study of the transition of animal remains from the biosphere into the lithosphere*. Thus, it was conceived as the detailed study of the processes and transformations undergone by an organism from its death to the fossilization of its remains.

Although this definition of taphonomy primarily dealt with Efremov's interest in the passage of terrestrial vertebrate remains from the biosphere into the lithosphere, subsequent uses of this approach to study different fossil assemblages broadened its application to other organic remains (plants, molluscs) and beyond the paleontological record. Indeed, it was within the field of archaeofaunal studies (see ZOOARCHAEOLOGY) that most nonpaleontological theoretical and methodological contributions to taphonomic research took place. In recent decades, archaeologists began to develop and systematize taphonomic frameworks to study nonorganic materials, such as lithic artifacts, on a regular basis as well (Hiscock 1985). Although not without dissent, archaeological practitioners of bone taphonomy support the current expansion of taphonomic perspectives towards the analysis of other materials of the archaeological record (see ARCHAEOLOGICAL RECORD).

Taphonomy can be broadly defined today as the theoretical and methodological scientific approach devoted to understanding the post-depositional (taphonomic) history of any fossil record (paleontological, archaeological, forensic, or other), considering all its

components, their spatial arrangement, and context (Domínguez-Rodrigo, Fernández-López, and Alcalá 2011). It seeks to identify the mechanisms and the sequence of events involved in the formation of any assemblage and its sedimentary matrix. Furthermore, it studies the processes of preservation and how they affect information in the fossil record (Behrensmeier and Kidwell 1985). Thus, taphonomy addresses the constant tensions between preservational and destructive media through the study of the record of these tensions on different materials (Borrero 2014a).

There is increasing recognition of the fact that every fossil record has been affected by taphonomic processes and that the impact of those processes needs to be properly evaluated in order to proceed with paleobiological or behavioral interpretation (see INTERPRETATION). Indeed, a taphonomic diagnosis is key to assessing bias and adjusting research questions to the characteristics and scale of the record under study. Or the other way around: if a taphonomic research is conducted at the landscape or regional scale, it guarantees the selection of the more adequate loci to answer specific research questions (Borrero 2014b; Burger, Todd, and Burnett 2008). Thus, from a taphonomic perspective, the transformations undergone by material remains within the process of fossilization are not only biased but also an additional source of information. Certainly, the widespread integration of taphonomic approaches in archaeological studies proved that most archaeological sites are better explained as cumulative, time-averaging, and dynamic phenomena (i.e., palimpsests exhibiting differential integrity, resolution, and preservation) rather than static well-preserved “living floors.”

Several basic concepts are the backbone of taphonomic approaches. *Agents* are the sources of energy (e.g., wind) that trigger different *processes* (e.g., transport). The latter modify the properties of material remains; such changes are known as taphonomic *effects*. Finally, *taphonomic history* is the sequence or order in which agents and processes acted upon an assemblage (Gifford 1981; Lyman 1994).

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Each taphonomic agent (e.g., wind, water, gravity, fauna, vegetation) originates manifold taphonomic processes (e.g., transport, sandblasting, dissolution, trampling, gnawing), which comprise physical, chemical, or biological mechanisms. These mechanisms impinge on the original attributes of remains. Within taphonomic studies, processes and their effects are separated into two general realms according to the context—before or after burial—in which they take place. *Biostratinomy* is the segment of taphonomic history that spans between the death of an organism and the final burial of its remains, while fossil diagenesis (see *DIAGENESIS OF BONE*) comprises the modifications occurring on remains after burial. Thus, since weathering (the physical and chemical decay of bone components) mainly occurs in subaerial contexts, it falls within the realm of biostratinomy, while bone mineralization and deformation are primarily diagenetic processes.

More generally, taphonomic effects on any fossil remain can be classified into two basic categories: *morphological* and *distributional* alterations. The former includes changes in the aspect, texture, shape, size, and so on of elements. The meaning of morphological effects in terms of formational history can be evaluated at the individual level (e.g., on an isolated specimen), although an assemblage approach is more informative. Examples of morphological modifications on different raw materials (bone, lithic, ceramic, wood) include polish, abrasion, fractures, tooth marks, cracking, root etching, weathering rinds, and coatings. On the other hand, distributional modifications transform the spatial arrangement of fossil remains. These phenomena encompass the movement of specimens and changes in their position—such as vertical and horizontal displacements, changes in the axial orientation, inclination, and inversion. Burial also modifies the distributional properties of the assemblages. Unlike morphological modifications, the assessment of taphonomic spatial changes is only feasible at the assemblage level. The study of taphonomic effects is essential for assessing the existence of taphonomic bias in fossil assemblages and identifying its possible sources.

Several factors determine the occurrence and characteristics of taphonomic effects. First, each environmental, sedimentary *context* exposes assemblages to differential conditions (i.e.,

potential taphonomic agents and processes). Therefore, researchers need to build any taphonomic study on a case-specific basis: identify the past and present agents that were locally available, the energy and magnitude of the processes they triggered, their signatures on different materials, and so on. Second, taphonomic effects vary according to the *intrinsic properties* of each organic or nonorganic element (i.e., physical and chemical attributes of remains). Thus, material-specific frames of reference are required to undertake the taphonomic study of every component of a multifabric record, as is the case of many archaeological assemblages (bones and ivory (see *BONES AND IVORY*), lithic, ceramic, metal, wood, etc.). Third, it is expected that the intensity and extension of taphonomic effects vary according to the *duration* of the process. Furthermore, given the sequential and cumulative nature of taphonomic effects, earlier processes in the taphonomic history of an assemblage may facilitate the subsequent transformations of remains by a different mechanism.

Taphonomic methods integrate the principles, knowledge, and case studies from natural sciences (biology, physics, chemistry, geology) with observations on the fossil record itself. Actualism is also central to most taphonomic research. Uniformitarianism principles, modern experiments (see *EXPERIMENT IN ARCHAEOLOGY*), and naturalistic observations provide jointly with natural sciences the frame of reference to assess taphonomically the patterns exhibited by the fossil record (e.g., Weigelt [1927] 1989). Hypothesis testing (see *HYPOTHESIS TESTING*) and the integration of data provided by other lines of evidence are common procedures in taphonomic research, since more than one agent and/or process produces the same trace or effect on material remains (equifinality). Therefore, competitive explanations are evaluated against a corpus of actualistic and fossil data to account for fossil trends.

The general goals of taphonomic studies within the realms of archaeological research have mostly focused on:

- assessing differential attrition to reconstruct the original content and patterns of material remains (see *DETERIORATION*);
- establishing agents of accumulation and modification as well as the sources of bias;

- detecting and describing common taphonomic trends at different spatial scales, whether to recognize background noise (e.g., the natural deposition of bones or taphonomic “bone rain,” geofacts or other lithic pseudoartifacts) or to identify sites or spaces that share their taphonomic properties (*isotaphonomy*);
- characterizing the taphonomic history of a fossil assemblage, that is, detailing the circumstances (sequence of events) under which the assemblage existed through time.

Taphonomy has become a powerful and necessary tool for disciplines dealing with the fossil record. Current research suggests that the incorporation of a taphonomic perspective improves the understanding of the sources of variation for every component of archaeological assemblages. Finally yet importantly, a widespread integration of taphonomy in cultural and natural resource management is highly beneficial for improving conservation policies and sustainable practices worldwide.

SEE ALSO: Archaeoentomology; Archaeometry; Charcoal and Wood Analysis; Conservation; Environmental Archaeology; Formation Processes; Geoarchaeology; Lithics Data Quantification; Marine Molluscs; Paleoethnobotany; Palynology

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Temperate Environments

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Temperate environments today comprise two global zones between the polar regions and Tropics of Capricorn and Cancer. However, to account for changes in time and space, here we define them as areas characterized by a common climate, with cool winters, warm summers, substantial precipitation, and consequently relatively stable ecosystems. They may have existed in parts of what are now equatorial regions during past glacial periods, but temperate environments are predominantly a feature of warm interglacial periods, which have periodically interrupted the generally cold conditions of the Quaternary period from ca. 2.6 Ma to the present.

There is only fragmentary evidence for older, pre-Holocene temperate (interglacial) environments. Subsequent glaciations and recent geomorphological processes, such as coastal erosion, colluviation, and alluviation, have removed sedimentary deposits containing fossilized remains of plants, animals, and cultural remains. Some of the best-surviving examples spanning the Late Quaternary (ca. nine interglacials in the last 650 kya BP) occur in Europe; for example, the Thames Valley terraces provide an extraordinary sequence of riverine deposits that have enabled reconstruction of the variable climate and environment. During Marine Isotope Stage (MIS)-11 at ca. 400 kya BP, their terrestrial biostratigraphic record indicates oak, alder, and hazel woodland with a fauna quite unlike today, including deer, horse, and bison, and extinct giant ox and giant deer, mixed with fauna representing a savannah-like environment, notably straight-tusked elephant, rhinoceros, and lion (e.g., Swanscombe). Elsewhere, lake sediments

provide complementary evidence of terrestrial and aquatic flora and fauna (e.g., Marks Tey). The last interglacial (MIS-5) experienced higher temperatures, more widespread tropical conditions, and higher global sea levels, but still offered greater prospects for floral and faunal expansion into areas uninhabitable during glacial periods.

Cycles of change can be recognized (Figure 1), with rapid warming events at the end of glaciations, followed by large-scale remodeling of continents due to sea-level rise (see SEA-LEVEL CHANGE), and in some areas land depression adding to flooding (see FLOODING) by marine transgression of vast expanses of land. Subsequent rebound has re-exposed some of these areas, making them progressively available for terrestrial life. Evolution of post-glacial landscapes occurred in terms of hydrology, landforms, recolonization of thermophilous species, vegetation succession, soil maturation, and faunal migration before decline occurred with progressive cooling, leading into the next glacial period. The cycle of appearance and decline is presumed relatively short, with MIS-11 lasting ca. 40,000 years.

The investigation of the Holocene (MIS-1), starting at ca. 11.7 kya BP, and previous interglacials relies on a multiproxy approach and the integration of numerous datasets. Temperate conditions show in the geomorphological and sedimentary record as fine-grained alluvial and estuarine deposits laid down by meandering river systems (see RIVER SYSTEMS), accumulations of organic layers and peats in marsh areas, and development of stable weathered soil horizons in drier terrestrial areas. This is in contrast to glacial-age deposits, typified on land by coarse unsorted river gravels and scree laid down by higher energy unstable conditions in an open, poorly vegetated environment (see GLACIAL AND PERIGLACIAL ENVIRONMENTS). The biostratigraphic record provides direct but fragmentary evidence of profound plant and animal responses to these major climatic and landscape changes.

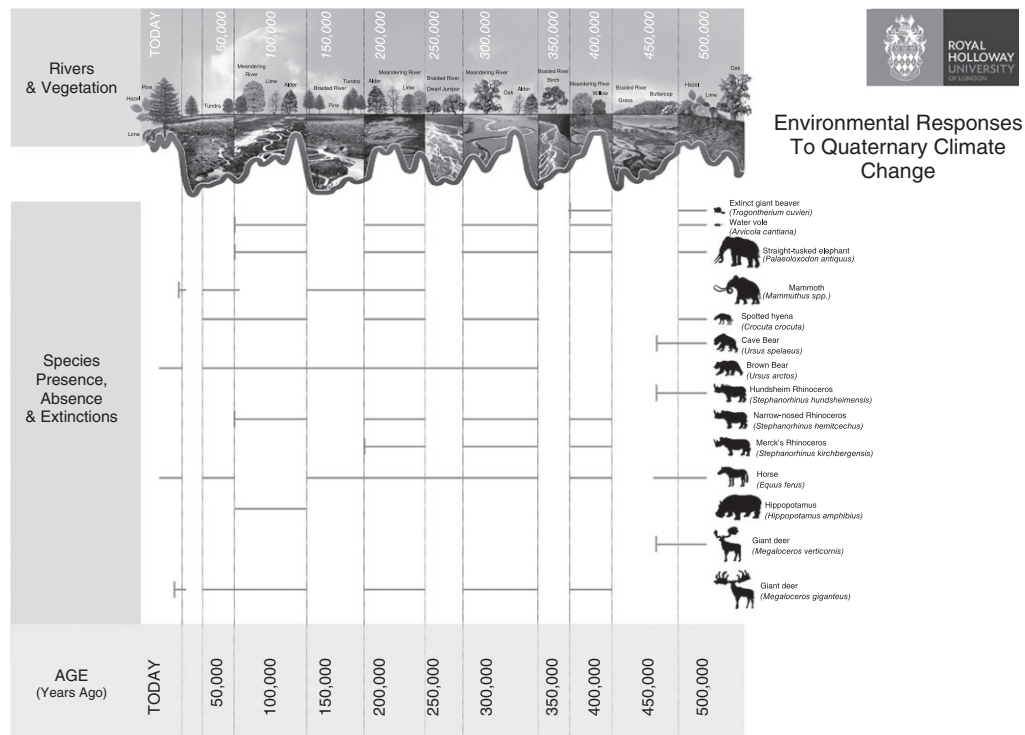


Figure 1 Environmental responses to Quaternary climate change.

Source: Republished with permission of Elsevier from Shreeve and Branch, 2010, "A Quaternary Timeline: A Teaching Tool for Interpreting Palaeoenvironmental, Palaeoclimatic and Archaeological Change over the Last 500,000 Years." *Proceedings of the Geologists' Association* 121: 83–86.

Holocene warming has not been linear or synchronous globally, with a series of minor climatic downturns and wetter (pluvial) periods identified through paleoecological and, more recently, documentary sources. A downturn at 8.2 kya BP has been suggested (Mayewski et al. 1997) and a Medieval Warm Period proposed for the tenth to fourteenth centuries CE, succeeded by the Little Ice Age from the fourteenth to nineteenth centuries, with a demonstrable effect on agriculture, settlement patterns, and society. For example, in Greenland and Iceland, expanding sea ice caused a shift in diet from agricultural to wild, and abandonment of marginal areas. Biostratigraphic data and accelerated sand dune formation indicate a Holocene thermal maximum at ca. 6.5 kya BP in North America, followed by a trend of cooling and wetness with the Neoglacial period beginning at ca. 4 kya BP, as supported by data from the Greenland ice core datasets.

Techniques used to study temperate environments

Holocene deposits provide information on landscape formation and modification, human economies, and subsistence. Their study highlights the challenges and complexities of regional climate and environmental reconstructions based on multiproxy records. The potential lines of investigation are manifold and constantly developing, with the following principal techniques used in isolation or combination to provide complementary information on any given aspect of reconstruction:

- Geoarchaeology (see GEOARCHAEOLOGY) helps identify areas of heightened potential for past human settlement, areas of human impact on the landscape, activity areas within sites, and route ways and sets a framework and

taphonomic context for paleoenvironmental and archaeological remains.

- Paleoenvironmental studies including paleoethnobotany (see PALEOETHNOBOTANY) contribute to reconstruction of landscape, human management, and exploitation of plant resources, including aspects of agriculture and diet (see VEGETATION MODELING USING POLLEN DATA).
- Zooarchaeology (see ZOOARCHAEOLOGY) provides data on past populations, including health, diet, disease, and privation, as well as species viability, adaptation, livestock breeding, management, and husbandry. The study of past insect, foraminifera, ostracod, and mollusc assemblages is useful in the reconstruction of local terrestrial and aquatic environments.
- Scientific dating methods such as radiocarbon dating, optically stimulated luminescence (OSL), uranium-series, and thermoluminescence (TL) techniques provide chronological control to the sedimentary and biostratigraphic records of human activity.
- Spatial and imaging techniques include use of light detection and ranging (LiDAR), infrared, and aerial photo interpretation, often managed within geographic information systems (GIS), to map past landforms, paleochannels, former coastlines, archaeological features, and monuments.

Major themes

Temperate environments are of key interest in the context of human lifeways, habitation, and migration because they offer a hospitable climate, and varied, relatively plentiful, plant and animal resources. Their study is of particular resonance given the global challenges and debate surrounding recent climate change and its triggers, drivers, timing, environmental consequences, and sustainability for humankind. The current emphasis in archaeological science is therefore on what the study of past temperate environments can teach us about dynamic change and adaptive strategies for plants, animals, and humans in the future. Key themes include the anthropogenic impact on the landscape through hunting, deforestation,

agriculture, urbanization, and interaction with climate change.

Biological responses to deglaciation inside and beyond the extensive glaciated zone were profound, but varied in timing, nature, and type. The spread of thermophilous plants is of interest. Pollen records from temperate southern South America indicate a vegetation response to widespread warming; for example, the expansion of *Nothofagus* forest in Tierra del Fuego (Rabassa et al. 2000). In northwest Europe, early recolonizers of open landscapes, such as birch and aspen, expand first in the archaeobotanical record, followed by encroachment of pine, alder, and then hazel within 500 years of the start of the Holocene. Denser deciduous forests followed, with significant impact on faunal populations, which shifted northwards. This had major consequences for human subsistence and settlement in an increasingly closed landscape with a changing resource base, and led to a series of responses including progressive changes in tool technology and the start of environmental control and clearance through burning from the Early Mesolithic period at ca. 11 kya cal BP onwards (e.g., Barnett 2009) (see ENVIRONMENTAL MANAGEMENT WITH FIRE). Dated fossil floral and faunal remains and biomolecular and genetic data suggest that Mediterranean areas with a southerly aspect—for example, southern France (Dordogne), Spain, and the European peninsulas—acted as glacial refugia, havens for warm-loving flora and fauna from which they could re-expand once climatic amelioration had begun (Tzedakis et al. 2003).

The timing of human arrival in the Americas is controversial, but dated remains associated with the pre-Clovis Miller complex lithic assemblage from Meadowcroft rock shelter, Pennsylvania indicate from at least 16 kya BP (Adovasio and Page 2002). A potential impact of this early colonization was the widespread extinction of megafauna, its timing first coincident with the end of the glacial period but also perhaps associated with overhunting by new arrivals, and most recently bison disappearance at the time of European colonization. There may have been a direct causal relationship or a more complex one related to land pressure, disease, and competition.

Dating of domesticates indicates that Neolithic agriculture arrived in the Mediterranean with a major human dispersal from Anatolia during

the Early Holocene at ca. 8.5 kya BP. However, recent DNA evidence suggests expansion from a Near-Eastern refuge as early as the Late Glacial at ca. 13 kya BP (Pereira et al. 2017), triggered by climate change and supported then by a hunter-gatherer lifestyle. The spread and adoption of agriculture and associated large-scale deforestation and habitat change of the Neolithic and Bronze Age periods are indicated by the appearance of domesticates, weeds, and more widespread grass and heathland habitats in the bioarchaeological record from ca. 6 kya BP in northwest Europe.

A period of Mid-Holocene rapid climate change from 6 to 5 kya BP in the Americas coincides with evidence for abandonment of sites (e.g., Atacama, Chile), continuous occupation (e.g., Catamarca, Argentina), and changes in subsistence practices—for instance, in food-gathering practices and exploitation of a wider range of environments to cope with increased aridity, for example grinding of wild *Prosopis* sp., *Schinus* sp., and *Geoffroea* sp. on the plains and/or piedmont of Mendoza, Argentina (García 2005). Arable and pastoral farming practice from historic times onwards has led to profound landscape changes in North America, notably in the Mid-West, where establishment of grassland prairies and areas of desertification has been recorded on a century-scale. Debate continues on whether agricultural and industrial developments over this period have had a significant impact on the course of current and future climate change.

Challenges and constraints

Key constraints to the study of temperate environments include a lack of suitable preservation environments, and their progressive degradation due to the impact of development, agriculture, and aggregate extraction. Loss of opportunity for recovery of suitable remains can occur through other natural or quasi-natural processes such as erosion, landslip, fluvial scour, and deep burial, causing problems of visibility and changing patterns of key depositional and preservational environments, such as the shift in arid versus maritime zones. The rate or patterns of these may increase with future global climate change, whatever its driver. Potential mitigation includes

targeted hydrological and ecological management of areas of waterlogged and marginal areas of known research potential, and designation and protection of key archaeological sites.

Chronological control can be problematic; also lack of funding for archaeology and archaeological science, lack of capacity and skills shortages due to a decline in those studying the subject at degree level, and a poor planning framework in many countries can lead to lack of adequate prospection, excavation, sampling, and mitigation against development or extraction and for the post-excavation analysis process to be minimized or lost.

Future directions

Further development of the fields of study and techniques described will continue to evolve and open up new opportunities for studying past environments and human-landscape relationships. In terms of understanding and adapting to future climate change, early prehistory (terminal Late Glacial to Early Holocene, equating to the Upper-Paleolithic to Mesolithic periods in most temperate zones) is seen as being of key importance in looking at ecological and human responses to major climatic transitions. The application of archaeological techniques to post-industrialization human impact on the environment (the Anthropocene) may become increasingly important in understanding feedback systems and habitat response to change.

SEE ALSO: Environmental Archaeology;
Paleoenvironmental Reconstruction

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Tephra and Volcanic Ash Analysis

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Volcanic ash (tephra) layers provide an invaluable record of volcanic activity and its impact on the environment. Tephra layers are widely used in archaeological research to provide chronological frameworks in extensive areas downwind of major volcanic zones throughout the world. Archaeological applications of tephrochronology range across all periods of human evolution, from the earliest Pliocene hominids in the Afar region of Ethiopia through to modern times.

The Icelandic geoscientist, Sigurdur Thórarinnsson (1944) established the terminology and principles of tephra studies and tephrochronology, and used the classical Greek word tephra (τεφρα) to define all pyroclastics (solid material produced by an eruption) erupted into the atmosphere, irrespective of particle size, shape, or composition. Tephrochronology originally described the use of tephra layers to correlate sediment sequences, but now includes all aspects of tephra studies, and a person who studies this is called a tephrochronologist. Tephra is produced from the fragmenting of magma in an explosive volcanic eruption. Tephra layers can range in thickness from several meters close to the source, to invisible cryptotephra consisting of a few grains per cm³ in distal areas.

Tephra isochrons

A primary airfall tephra layer is formed in a geological instant (usually days, or at most weeks) and so reflects a discrete and short-lived moment in time. If the tephra layer can be followed spatially, identified and correlated between sites, it becomes an isochron. The base of the tephra layer represents a comparable moment in time

wherever that isochron occurs. The unambiguous identification of an isochron allows its date to be transferred to every location where it is found. This can be crucial when trying to establish correlations, synchronicity between, or the order of, events. This ability to carry dates to new locations means that tephra layers can provide an independent means of checking other dating techniques (see DATING IN ARCHAEOLOGY).

The archaeological significance of tephrochronological isochrons is demonstrated in Iceland and New Zealand by distinctive tephra layers which are coincident with the arrival of people. Iceland was settled in the mid to late ninth century AD and based on medieval written records derived from oral history; the traditional date given for this is 874 CE. Archaeological research has shown that the settlement of Iceland is coincident with a distinctive two-colored tephra layer, consisting of a white lower component, sourced from the Torfajökull volcanic system, and a much more widespread upper olive green tephra, erupted from the Veiðivötn volcanic system. This tephra layer, often termed the “Settlement Layer” or the Landnám Tephra Layer (LTL), provides a widespread isochronous marker in soil, peat, and lake sediments, which essentially divides an Icelandic environment without people below the layer, to the one above, where the impact of human settlement can be studied. The LTL is found in Greenland ice cores and is dated to around 877 CE (Schmid et al. 2017).

The dating of the settlement of the New Zealand archipelago has been controversial, with older dates based on radiocarbon analysis being at odds with numerous other evidence for the arrival of people some 700 years ago. Tephrochronology has played a major role in resolving this debate, with the recognition that the distinctive white Kaharoa Tephra (1314 ± 12 CE; Hogg et al. 2003) in the eastern and northern part of the North Island is found below all of the reliable archaeological and paleoenvironmental evidence for the arrival of people.

Tephrochronology relies on the Law of Superposition, where younger sediments are deposited

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sequentially over older ones. Establishing the stratigraphic relationships of tephra layers is termed tephrostratigraphy. Tephrochronology, wherever it is applied, relies on identification, correlation, and dating of tephra layers. In terrestrial sequences, the tephra layers occur in soils, lake sediments, peats, glaciers, and even in archaeological deposits.

The physical properties of macroscopic tephra layers play an important part in the characterization of a layer. The chemistry of the magma is responsible for the color of the glass and mineral components and therefore the color of the tephra layer. Particle size of a tephra layer will decrease with distance from the volcano and away from the main axis of fallout, and can be semi-quantitatively assessed by describing the tephra as “fine, medium or coarse,” or can be measured quantitatively by sieving or using a particle size analyzer.

Archeologists can also utilize less than “ideal,” disturbed tephrostratigraphies. Dugmore and Newton (2012) state that “total tephrochronology” includes disturbed or missing tephra layers, or layers that show evidence of reworking, in order to fully understand a landscape at the time of tephra deposition. Environmental archaeological research benefits from the better understanding of vegetation cover, landscape disturbance, erosion and human impacts that these less than “perfect” layers provide.

Some volcanic eruptions, either submarine or ones close enough to a coast, can produce large (cobble-grade) fragments of pumice, which can float on water and be transported thousands of kilometers by wind and ocean currents. For example, multiple Holocene eruptions from the Katla Volcanic System, southern Iceland, have produced pumice which ocean circulation has spread around the North Atlantic basin from North America to NW Europe. The pumice is found in coastal archaeological sites in Arctic Canada, Greenland, the British Isles, Scandinavia, and Iceland. Some of this pumice was used as an abrasive tool for smoothing wood, antler, bone and animal hides and as fishing floats. Thus, pumice can form part of the artifactual record of past human societies, as well as contributing to site chronology.

Cryptotephra

Traditional tephrochronology uses visible tephra layers in areas close to volcanic activity, such as in Iceland, Japan, New Zealand, Central America, and Alaska. However, it has long been known that tephra from eruptions can travel great distances. As early as the 1960s, tephra layers were identified from Atlantic sediment cores and from peats in Scandinavia. The work of Dugmore (1989) and coworkers in the late 1980s clearly established that Icelandic tephra layers occur in Scottish peat deposits. They also recognized their potential in paleoenvironmental and archaeological research (see PALEOENVIRONMENTAL RECONSTRUCTION). These far-travelled tephra are not visible to the naked eye, and so the term cryptotephrochronology is used to signify that the layer is hidden (Davies 2015). Cryptotephra can occur in peats, organic silts, lake sediments, ice cores, and even cave deposits and rock shelters. The number of shards per gram may vary from many thousands to less than 10 shards per cm³, with particle sizes usually less than 125 microns and as small as a few microns.

As cryptotephra layers are not visible to the naked eye, a variety of techniques are required to detect them. X-radiography and magnetic susceptibility, combined with XRF core-scanning, can be used. Incineration can isolate tephra grains from organic material, while mineral acid digestion can also remove organic matter. Where the tephra are mixed with high concentrations of inorganic material, density separation/flotation techniques utilizing liquids of specific densities are employed. Sieving can also increase the concentration of fine-grained cryptotephra.

Once isolated, the tephra grains are then generally mounted on a microscope slide and counted under an optical microscope. The isotropic property of volcanic glass shards helps to differentiate volcanic glass from other detrital material, such as quartz. Volcanic glass shards can also have a distinctive appearance ranging from platy to pumiceous, with numerous vesicles. These morphological characteristics help to differentiate the glass shard fraction of a tephra layer from other detrital mineral material. Characteristic volcanic minerals may also be present.

Cryptotephrochronology is widely used in archaeologically related paleoenvironmental studies, particularly in wetlands. In the British Isles, numerous tephra layers occur in Holocene peatlands, especially in Ireland and Scotland, and are routinely used in constructing chronological frameworks in studies of landscape change, human impact, and human–environment interactions. Although mainly sourced from Iceland, Alaskan tephras are also present. Other examples include the 39 ka Campanian Ignimbrite tephra, which has proved to be an invaluable isochronous marker horizon across southeastern Europe at the time of the Middle to Upper Paleolithic transition, and the late glacial Laacher See tephra, an important Allerød isochron in northern Europe.

Dating

Dating of tephra layers depends on the age of the tephra and its context. Depending on context, Late Quaternary and younger tephras are dated by a range of methods including written records, radiocarbon dating of associated organic matter, linkage to dendrochronology, or by the presence of the tephra layers in incremental records such as ice cores or varved sediments (see VARVE CHRONOLOGY).

Written records give the most accurate and precise calibration method. In Iceland, an excellent post-settlement historical record of volcanic activity exists. This has allowed the development of a robust and high-resolution tephrochronological framework, utilized routinely by archaeologists.

Although radiocarbon dating of tephra layers is common, tephras also provide an independent check of radiocarbon dates. The isochronous nature of tephra layers means that an accurate and precise date is transferred to anywhere that tephra is found. Tephras dated by historical records, radiocarbon dating, or ice core ages can also be an integral and valuable part of Bayesian dating frameworks.

Ar–Ar dating (see ARGON–ARGON DATING) is the most common means of directly dating tephra layers. For example, the massive Younger Toba Tuff (YTT) is dated from Middle Paleolithic

archaeological sites in India to 75.0 ± 0.9 ka (Mark et al. 2014).

Tephra geochemical analysis

It is preferable to analyze individual tephra grains, and in many cases the glass fraction is studied. A smooth cross-section of the tephra grains is required for geochemical analysis, and tephra samples are incorporated with resin either into a block or onto a microscope slide, and ground and polished to create a smooth cross-section of the tephra grains.

Major and minor element oxide abundances are frequently acquired using electron microprobe analysis (EMPA). An electron microprobe is a dedicated instrument designed to obtain quantitative geochemical analyses using wavelength dispersive spectrometry (WDS), but it is also possible to use a detector using energy dispersive spectrometry (EDS) attached to a scanning electron microscope (SEM). The former is preferable for accuracy and precision, while the latter is faster and cheaper and sometimes the only means of analyzing the smallest tephra shards.

Major and minor element geochemistry is not always able to discriminate between tephra layers from the same source, but trace element abundances often can. Laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS) is most frequently used to obtain trace element concentrations, and uses a fine resolution laser (as small as a few microns in diameter) to ablate material from a tephra grain, which is ionized and measured in a mass spectrometer.

SEE ALSO: Archaeological Volcanology; Dating in Archaeology

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Testate Amoeba Analysis

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What are testate amoebae?

Testate amoebae are a group of amoebae that produce a shell (called a “test;” Figure 1). These organisms have also been referred to as shelled amoebae, testaceans, arcellaceans, or rhizopods, but these terms are now not preferred. Testate amoebae belong to at least three unrelated groups of organisms: Euglyphida, Arcellinida, and Amphitrematidae. However, for application in bioindication, paleoecology, and archaeology, these three groups are generally treated together as they play similar functional roles and produce decay-resistant shells of similar size ranges (mostly ca. 20–150 μm). Testate amoebae are mostly heterotrophic organisms feeding on bacteria, fungi, other protozoa, microalgae, and in some cases even microscopic animals such as nematodes and rotifers. A few species, living in either acidic *Sphagnum* peatlands or lakes, bear symbiotic algae and are thus also photosynthetic. Testate amoebae are common in lakes, rivers, peatlands, and soil, and to a lesser extent in brackish water. They are quite diverse: ca. 2,000–3,000 species have been described, but recent molecular studies are revealing a wealth of hidden diversity.

Applications of testate amoeba analysis in paleoecology

Different testate amoeba species have different environmental preferences and the shells of testate amoebae allow species identification even after the organism is dead, thus making it possible to use them to infer past

environmental conditions (Charman 2001). The most widespread applications of testate amoebae have been for the reconstruction of the past wetness of peatland sites (see PEAT DEPOSITS) as a proxy for hydroclimate. Other applications involve the reconstruction of sea-level change (see SEA-LEVEL CHANGE) from coastal sediments and aquatic pollution (see WATER POLLUTION) from lakes (see LAKE DEPOSITS).

Not all shell types preserve equally and such taphonomic bias should be understood when using these organisms in paleoecology or archaeology (Mitchell, Payne, and Lamentowicz 2008; Wilmschurst, Wiser, and Charman 2003). The shells of genus *Euglypha* (Figure 1a) and related euglyphids are the most fragile. These shells are constructed of delicate siliceous plates and are typically only found in optimal depositional conditions (Payne 2007; Swindles and Roe 2007). By contrast, the shells of genus *Assulina* (Figure 1i), which are also made of siliceous scales but overlain by an organic coating, are among the most resistant of all testate amoebae. Taxa producing proteinaceous shells (e.g., *Hyalosphenia*, *Arcella*) are usually very resistant (Mitchell et al. 2008).

The preparation of samples for testate amoeba analysis depends to some extent on the substrate type, but generally requires wet sieving to remove the coarse material (usually $>150\ \mu\text{m}$). Some methods also recommend subsequent sieving to remove fine material (usually $<15\text{--}20\ \mu\text{m}$), retaining the intermediate fraction (e.g., $15\text{--}150\ \mu\text{m}$). Some very small species (e.g., *Trinema lineare*) can be lost when using fine sieving, but the big advantage of this step is that it removes fine sediment, which can make up a substantial proportion of the substrate in some contexts. Smaller species may, however, be ecologically meaningful and by using this sieving method loss of useful information can occur (Payne 2009). Slides are prepared for microscopy using a mounting medium such as glycerol and inspected at magnifications typically of 2–400 X. The number of shells to be counted depends on the degree of precision of ecological information

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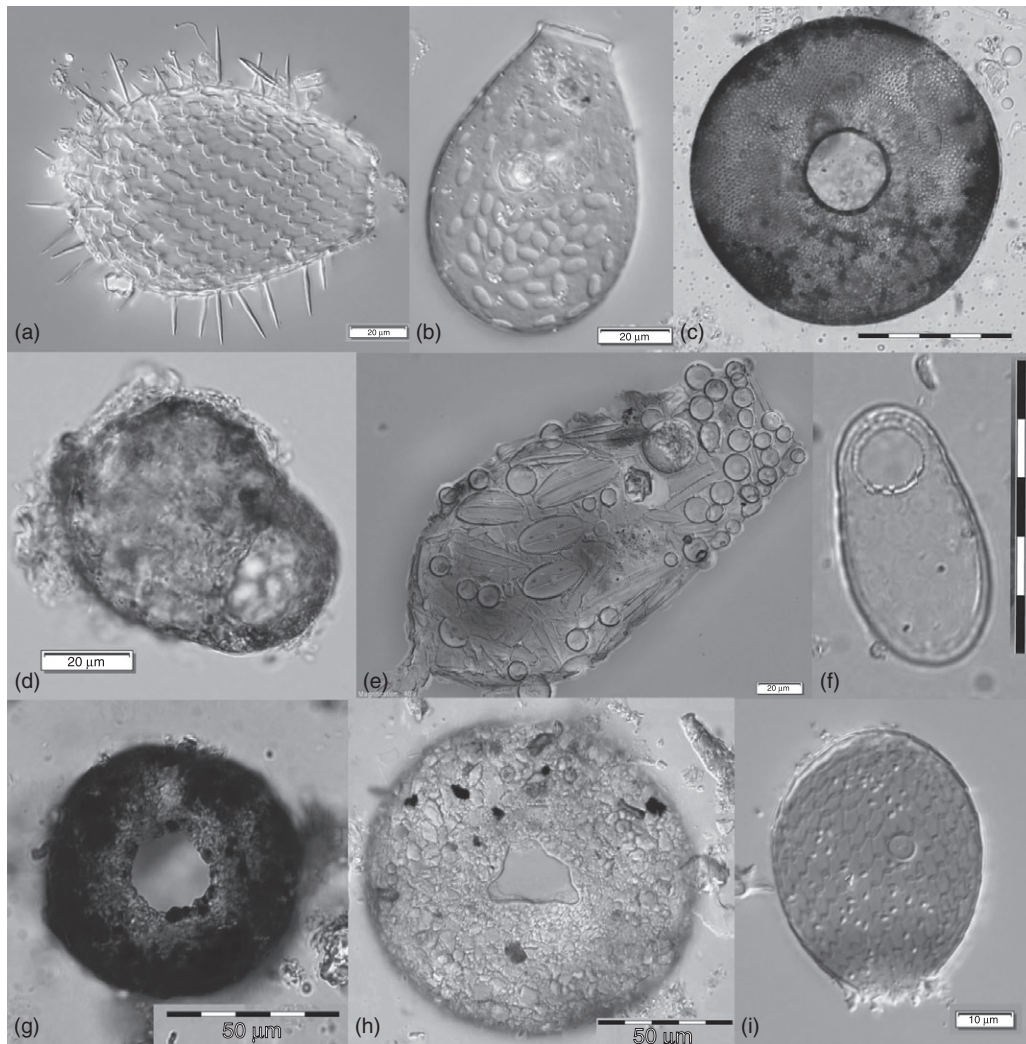


Figure 1 Some of the diverse range of testate amoebae identified in paleoecological and archaeological studies. (a) *Euglypha ciliata*-type; (b) *Nebela tinctoria*-type; (c) *Arcella discoides*-type; (d) *Centropyxis aerophila*-type; (e) *Diffugia oblonga* (PenardCollection, Natural History Museum of Geneva, Image from Wikimedia commons, https://commons.wikimedia.org/wiki/File:Collection_P%C3%A9nard_MHNG_demo_sample.tif); (f) *Trinema enchelys*-type; (g) *Cyclopyxis kahli*; (h) *Trigonopyxis arcula*; (i) *Assulina muscorum*. Scale bars: a, b, d, and e, 20 µm; c, f, g, and h, 50 µm (10 µm per increment); i, 10 µm.

required. The general goal is to count 150 shells, but it has been suggested that lower numbers, for example, 50, can provide useful ecological information (Payne and Mitchell 2009). If rare species are considered useful then their presence and abundance can only be estimated using much higher counts. The use of contrast-enhancing microscopy such as phase contrast or differential

interference contrast is very useful to spot and identify transparent species such as the genera *Euglypha*, *Trinema*, and *Corythion*. There is unfortunately no single up-to-date and user-friendly identification guide to testate amoebae. Many references are either out of date or focus solely on a small number of species, and guides are published in many languages.

Applications of testate amoeba analysis in archaeology

The application of testate amoeba analysis is currently well established in paleoecology but less so within archaeology. Despite generally limited application, there are several situations where testate amoeba analysis has the potential to make a substantive contribution to archaeological research. The first of these is through the role of testate amoebae as a proxy for the reconstruction of past climate change. Testing hypotheses regarding the role of climate in driving human social and cultural change often requires an understanding of climate change at a local and regional scale. Paleoclimate reconstructions using testate amoebae can help provide this information. Sites with paleoecological potential for testate amoeba studies are relatively widespread in the temperate and boreal zone, often allowing climate reconstructions in the vicinity of archaeological sites of particular interest. An example of this is for understanding apparent Bronze Age depopulation of the uplands of southwest England. Amesbury et al. (2008) used testate amoeba analysis to understand regional climatic change, proposing evidence for a climatic deterioration (ca. 1150–1400 cal. BCE) and drawing linkages with the established archaeological record. Used in combination with other methods, testate amoeba analysis has the potential to help untangle the complex links between environmental change and changing human societies.

Within the context of archaeological sites themselves, testate amoebae have been most widely used in wetland archaeology. In wetland sediments, testate amoeba shells are often well preserved, offering potential as indicators of past environmental conditions. For instance, Gearey and Caseldine (2006) applied testate amoeba analysis to a multiphase archaeological site in southern Ireland to reconstruct change in peatland surface wetness. Their results suggested a long-term correlation between archaeological usage and wetness, with more construction of features such as trackways in drier phases of the bog's history. This is information that would be difficult to obtain by any other means. A related potential application could be to understand human impacts on peatland environments. For

instance, it is probable that many water-table drawdown events recorded in paleoecological records may represent human activities such as peat cutting or drainage. While this research direction has yet to be explored in detail, it is probable that testate amoeba analysis could cast light on human exploitation of wetland environments. Similarly, there is the potential for testate amoeba analysis to provide contextual information regarding archaeological artifacts found preserved in peat. A particular example of this is the bog bodies that have been widely found preserved in peatlands across northwest Europe. Plunkett et al. (2009) discuss the use of testate amoeba analysis as part of a multiproxy approach to understand the depositional environment of such a bog body in central Ireland. Their results showed that the depositional environment of the find was most likely a shallow pool. Testate amoebae may be recovered from a broad range of archaeological samples. There is a single record of testate amoeba analysis from an Egyptian mummy (Chardez and Lambert 1988). Fourteen testate amoeba tests belonging to five species (*Centropyxis aerophila*, *Plagiopyxis callida*, *Plagiopyxis declivis*, *Phryganella acropodia*, and *Nebela parvula*) were recovered from three dust samples. These species are frequently reported from soils and the morphology of these ancient specimens was indistinguishable from modern taxa. Such studies may allow insights into the life history and depositional environments of such artifacts.

A final use of testate amoeba analysis is as part of a wider suite of non-pollen palynomorphs (NPPs). Many testate amoeba shells are destroyed by the chemical treatments required in preparing samples for pollen analysis. However, some of the most robust tests, such as those of *Arcella* and *Archerella*, can survive and be encountered in pollen slides. An increasing proportion of palynological studies are aiming to quantify the diverse range of NPPs found in such samples, including testate amoebae. Payne et al. (2012) reviewed this literature and identified more than 50 palynological studies that had included testate amoebae, with several of these from archaeological contexts. While testate amoebae were not the focus of these studies, many nevertheless found that identifying testate amoebae yielded useful additional information. While pollen preparation methods

cannot be recommended for studies specifically aiming to quantify testate amoebae, the enumeration of testate amoebae in pollen-focused studies is a sensible approach, as the most abundant taxa are easily identifiable and provide useful contextual information (Payne et al. 2012).

It is clear that testate amoeba analysis has a great deal to contribute to archaeology, particularly in the wetland environments where testate amoebae are most abundant. This potential has currently only been exploited to a limited degree and much more could be achieved.

SEE ALSO: Hydrological Modeling;
Palynology; River Systems

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Urban Environments

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The rise of towns and cities was one of the most important developments of humankind. It not only was a major step in social evolution but also led to great changes in people's living conditions. Urban areas developed in different periods of prehistory and in historical times, in different geographic and climate locations, on lands with specific geomorphological conditions, and with specific opportunities and constraints, such as the availability of natural resources. The size and structure of the built environment also varied. Cities developed from different roots, such as military bases, seats of political power, religious centers, or centers of trade, craft, and industry. Despite these differences, urban areas have some distinct common features. Because they bring many people together, the land is densely built-up and supports some common arrangements and structures. Most of the population is not engaged in agriculture, so the main sources of food are grown in surrounding rural areas or are imported from further afield. Populations living in cities tend to be clearly structured according to social and economic status and occupation. Living in large centers generates specialized economic activities that in the past were clearly assigned to specific urban areas (e.g., markets, manufacturing areas, services). Densely populated and intensively built-up land influences local climate, and hydrological and biogeochemical cycles in different ways, and results in nutrient enrichment, and air (see AIR POLLUTION) and water pollution (see WATER POLLUTION). Such areas also support specific flora and fauna. All the above factors are important variables when studying the past urban environments from remains found in archaeological sites.

Both archaeology and natural sciences are developing our knowledge of how the urban areas of the past grew and functioned. The results

obtained concerning the natural environment are dependent on both the preservation of urban strata and understanding the sources and taphonomy of the remains recovered. Urban sites have usually been occupied for hundreds or even thousands of years. As a consequence, thick deposits with dense, complex stratification occur. In multiperiod sites, the older strata are frequently destroyed and truncated by younger structures, and different items may be redeposited as a result of human activity or natural processes. In contrast to archaeological artifacts which may be more or less definitively assigned to particular periods based on their typology, biofacts cannot be dated based on their form or type; direct dating by radiometric means is required. Therefore, well-sealed, closely dated stratigraphy is a basic prerequisite for the investigation of animal and plant assemblages, as well as for other traces of past environments. The taphonomy (see TAPHONOMY) of the subfossil assemblages of different groups of organisms in urban sites is especially complex and diverse, as it depends on both biological factors, such as the biology of the species being studied (e.g., diaspore productivity) and the resistance of their tissues to decay (see DIAGENESIS OF BONE and FORMATION PROCESSES), and the types of archaeological features and specific depositional processes at the site. The means of preservation (waterlogging, carbonization, mineralization, desiccation) have specific selective effects which have to be considered when interpreting both qualitative and quantitative data. Multiproxy studies provide the best means of diminishing the negative effects of the loss of information on past environments resulting from fragmentary preservation of the subfossil assemblages and biases of particular data types. By combining different methods it is possible to fill at least some gaps in a paleoenvironmental record.

There is a long tradition of the use of paleobotanical methods (see PALEOETHNOBOTANY) not only to gain knowledge on plant use, but also to reconstruct past urban environments. This is based on an assumption that the composition of wild flora depends on a number of

natural and cultural factors. The most thorough reconstructions of the urban flora and vegetation are made through the analysis of waterlogged fruits and seeds, which usually occur in great abundance and variety. Plants and plant communities are first and foremost perfect indicators of the whole range of soil and hydrological conditions and land-use. Using the ecological characters of plant taxa (e.g., the ecological numbers by Ellenberg et al. 1992), it is possible to define features of past habitats and to trace their transformation through time. Such reconstructions may concern specific locations within the urban space and are usually based on the results of analysis of a series of archaeobotanical samples from a site. It has been shown also that if the dataset is large enough, plant remains dispersed in unspecific cultural layers in different parts of an urban area can be used to detect even discrete changes in the ecological conditions (Latałowa, Badura, and Jarosińska 2003).

Pollen analysis (see PALYNOLOGY) of urban strata (on-site data) also has great potential for reconstructing the local natural environment, especially if non-pollen palynomorphs (NPPs), which include fungal spores, some algae, and cyanobacteria, elements of protozoans and invertebrates, are considered. This group of microfossils is invaluable in supplementing information on the local ecological conditions and some kinds of human activity, providing information on the vegetation of a site as well as presence of, for example, hay, fodder, or animal dung.

Where naturally infilling lakes (see LAKE DEPOSITS) and peat deposits (see PEAT DEPOSITS) are found within an urban area or its neighborhood (off-site data), pollen analysis can provide information on extra-local vegetation and the environment outside a town. As the areas around cities were a source of the raw materials and were used for food production, urbanization contributed to their transformation. Off-site pollen analysis can be used to detect these changes, such as the rate of deforestation, changes in forest composition, and agricultural practices.

Irrespective of period and geographical factors, the rise of any city leads to environmental change. In a growing city, patches of natural and seminatural vegetation gradually shrink, and are replaced by anthropogenic plant communities, often one

of lower taxonomic diversity and dominated by cosmopolitan species. Particularly, typical urban vegetation includes nitrophilous communities that grow on strips of ground beside buildings and moats, or near latrines or concentrations of waste. Also, vegetation typical of trampling places (pathways, streets) and disturbed soil are usually fairly common in urban sites. Gardens within urban areas are used mainly for growing vegetables, herbs, ornamental plants, and fruit trees and provide habitats for weeds. Gardening and transportation of imported goods into the town are the main routes for the introduction of alien species. Therefore, urban areas were, since their very beginnings, centers for synantropization of flora, reflecting the dynamics of long-distance trade and cultural contacts. Urban faunas are also distinct. A number of studies have demonstrated a clear relationship between faunal assemblages, the structure of a town, and an advancement of the urbanization process. Zooarchaeological studies (see ZOOARCHAEOLOGY) undertaken for the purpose of paleoenvironmental reconstruction of urban sites are based mainly on analyses of insect and microvertebrate remains. The structure of microvertebrate populations within urban environments is dependent on the arrangement of an urban space, such as density of buildings, presence of green areas, and methods of food storage. For example, in the densely built ancient cities of the Near East, more than 2,500 years ago, species-poor communities of small mammals (dominated by the house mouse *Mus musculus domesticus*) developed that are similar to those found in the densely populated core areas of modern cities (Weissbrod et al. 2014). Insect assemblages studied in different features and contexts within an urban site can show the relative abundance of both indoor and outdoor habitats and may illustrate, for instance, hygienic conditions, presence of grain pests, or an abundance of rotting matter. Different aspects of assemblages of various groups of insects in urban environments have been discussed by Kenward and Allison (1994).

Geoarchaeology (see GEOARCHAEOLOGY) is another important, but still not widely used, source of data on past urban environments. By using micromorphology (see MICROARCHAEOLOGY) to study deposits exposed in archaeological excavations it is possible to reconstruct modes

of formation of stratigraphic sequences in great detail and assess the character of the in-situ human activities and natural events that have produced these deposits. This method is still useful even where different post-depositional, pedological processes have obliterated stratigraphical detail and the deposits appear amorphous, as has been shown by studies on the origin of the early medieval dark earth deposits found in many European urban contexts (Macphail, Galinié, and Verhaeghe 2003). Geochemical analyses (see CHEMICAL MAPPING) can also be used to characterize the use of urban space, for example the location of different crafts, waste deposition, and animal housing, as well as detection of water and soil pollution, including heavy metals (Oonk, Slomp, and Huisman 2009).

The development of cities was also closely related to water resource availability. The scale and the way in which people altered or managed water resources varied greatly depending on local conditions: for instance, the construction of aqueducts in many Roman towns to overcome water shortages and, in contrast, drainage and ground reclamation in towns built up along sea shores or in river deltas (e.g., terps). Use of water for mills altered local hydrology, while different crafts (e.g., tanning) and sanitation (sewage infrastructures available or not) degraded water quality. Moreover, paved and trampled surfaces were impermeable to rainwater, which then transported pollutants and waste into streams, rivers, or other water-bodies. Eutrophication of water and heavy metal pollution of water, soil, and air (see POLLUTION AND HERITAGE CONSERVATION) had negative impacts on the cities' environments and on human health. In the crowded and poor sanitary conditions in towns, intestinal parasites and other diseases could flourish. As the eggs of common parasites (see PARASITE OVA AND CYSTS), such as whipworm (*Trichuris*) and mawworm (*Ascaris*), are usually observed in prepared pollen samples, pollen analysis from urban contexts or water bodies situated within an urban area may help in evaluation of the level of intestinal parasitic diseases in a local population.

Analysis of human remains (see BIOARCHAEOLOGY) can reveal much about past urban living conditions as well. Mortality rates, and dental and osteopathological diseases can show the effects

of poor diet, prolonged or recurring periods of famine, and environmental pollution.

Overpopulation and overuse of land, and climate change—especially drought—are understood to be among the possible causes of the collapse of some cities, concurrent with a fall of ancient states (e.g., the Maya). The role of environmental crises, as compared to political and sociocultural factors, in such declines is a matter of debate (Butzer and Endfield 2012). There is, however, no doubt that the environmental conditions were of crucial importance for both the establishment of a city and its successful functioning. Interdisciplinary research involving archaeology and different disciplines from natural sciences allows us to investigate and understand these uniquely human environments further.

SEE ALSO: Air Pollution; Bioarchaeology; Chemical Mapping; Diagenesis of Bone; Formation Processes; Geoarchaeology; Lake Deposits; Microarchaeology; Paleoenvironmental Reconstruction; Paleoethnobotany; Palynology; Parasite Ova and Cysts; Peat Deposits; Pollution and Heritage Conservation; Taphonomy; Zooarchaeology

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Use of Biological Collections

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The basic methodology for identifying biological remains from archaeological sites (“biodata”) relies on comparison of unknown material with specimens of known identity. Such known specimens exist in biological collections, held, for example, in museums and archaeological science laboratories. The term “reference collection” is often used for the latter, with the implication that the material is specifically for comparison. Common types of reference collection include seeds, pollen, phytoliths, wood and vegetative anatomy, animal bones, teeth and antlers, animal hair and skin, shells, and insects. Although still primarily gathered for morphological and anatomical comparison, biological collections have also become important as a source of DNA and for other chemical analyses, such as stable isotope investigations.

The initial sorting and identification of biodata can be carried out using printed and online manuals, but actual reference materials are essential to verify and determine more difficult identifications. Reference collections are also used to identify subsidiary parts of an organism, for example, cereal chaff or fruit stalks; and specimens with detailed provenance can give further insights, for example, teeth from known-aged animals can be used to age archaeological specimens.

National and local museums can contain many millions of biological specimens. These collections may not be designed as reference collections for use within archaeology, but they remain an essential resource for specialist work. Full acknowledgment and citation of any

specimens used as part of archaeological research should be given. Curators can also provide advice on collections care.

Forming a reference collection

Collecting and curating reference material can be time-consuming and expensive. A long-established laboratory may have thousands of specimens, many gathered directly from the field, with dedicated staff time for curation. A new laboratory or independent researcher will often start by focusing on common taxa. The concept of a “distributed collection” is increasingly being explored (e.g., Fairnell and Orton 2017) in which collections are owned and housed individually, but are databased centrally, enabling workers in one institution to locate relevant material in others.

The range of taxa to be included in a reference collection will depend on the geographical study area and time frame of interest. The biota found in the region of interest today is the obvious starting point, but over time, different species will have been present. It may therefore be necessary to look further afield to find relevant comparable, surviving biotas.

The focus of a collection will also depend on the expected preservation of archaeological material; for example, if waterlogged or desiccated plant remains are likely, a wide range of vegetative plant parts will be required, in addition to fruits and seeds. If agricultural sites are the focus, then good representation of crop varieties and farm animal breeds will be desirable. Collection of reference material can be easily integrated with ethnoarchaeological work, for example, collecting by-products of crops or animal-carcass processing.

Obtaining specimens

Reference material should be accurately identified and in good physical condition. Plant parts

such as seeds and wood are ideally vouchered by a herbarium (pressed plant) specimen bearing leaves, flowers, and so on, that can be identified by a botanist and be available for future taxonomic investigations. An insect can be preserved whole and form its own voucher. For animals such as mammals and birds, a digital image of the carcass is required before preparation.

Fieldwork for acquisition of reference material should be planned to optimize the timing, for example, to coincide with flowering season or breeding condition. Protected areas, such as nature reserves and official enclosures, can be very productive. Collecting in the vicinity of an excavation has the benefit of increased understanding of the geomorphology and vegetation, which will be valuable in interpreting biodata.

Reference material can also be acquired or donated from existing collections, for example, botanical gardens or gene banks, although the quality of such specimens should be assessed. With such material, it is advisable to have two or three different accessions for a species so they can be checked for consistency in identification. Good documentation is important; confirmation should be sought that the material offered was legally acquired and is the property of the donor.

Ethical and legal aspects

Collecting or exporting plants and animals may require permission from national or local representatives. Plants and animals listed by the Convention on International Trade in Endangered Species (CITES) will usually require both an export and import permit. When collecting is planned, it is advisable to get advice from local museums and field biologists. Collectors should also be aware of ethical aspects of collecting, for example, relating to rare plants and animals or recording of indigenous knowledge.

Preparation and storage

Plants and fungi

Plants are usually vouchered by a herbarium specimen. Macroremains such as seeds, fruits, and vegetative parts are collected into paper or

cloth bags so that they can dry without going moldy. Fruit stones embedded in fleshy fruits should be extracted before the fruit dries. Once plant materials are dry, they should be frozen at minimum -20°C for one week to kill any insect infestation. Seeds are usually kept in glass tubes or archival (e.g., polystyrene) plastic boxes in shallow drawers to allow easy browsing. Woods may be sectioned for anatomical slides, or charred for examination under an epi-illuminating microscope. Waterlogged archaeological material can be stored for reference use, either freeze-dried (risking some loss in definition) or wet in 70 percent ethanol or industrial methylated spirits (IMS), or sectioned on microscope slides using suitable mountants.

Microremains are usually also held on microscope slides, using permanent or semipermanent mountants. Starch granules (see STARCH GRANULE ANALYSIS) can be extracted from dry plant material by grinding. Pollen can be extracted from fresh or dry flowers using a brush. Phytoliths (see PHYTOLITH ANALYSIS) are extracted by ashing plant material in a muffle furnace, or treating with acid in a suitably equipped laboratory.

Plant DNA is usually extracted from leaves or seeds. It is routinely extracted from herbarium specimens up to 200 years old. However, if DNA extraction is desired from new collections, fresh leaves should be collected into paper bags, then packed in sealed plastic bags with silica gel to maintain a dry environment. If plant collections are treated with alcohol this will destroy any DNA within (Doyle and Dickson 1987).

Vertebrates

Animals should be identified to species, sex, and age, before the carcass is prepared for its skeletal and/or other relevant parts. Fresh carcasses of known animals are best, because they are easier to identify and handle.

The four main methods of bone preparation are burial, cold-water maceration, hot-water maceration, and dermestid beetles. The choice of which method to use often involves a compromise between time and smell. The quicker processes, hot-water maceration and beetles, can be the smelliest. Enzymes, such as Neutrase® and trypsin, can be used to help break down

the protein (flesh); biological washing detergents (which contain enzymes and mild bleaches) can be used to help break down protein and fat; fat can also be removed with the use of solvents, for example, acetone. Whichever method and chemicals are used, a risk analysis must be carried out beforehand to make sure the preparation is carried out safely. Fresh carcasses may be a source of zoonotic disease, such as avian flu; dermestid beetles need to be housed and cared for appropriately; and all chemicals must be used safely, following, for example, the United Kingdom's Control of Substances Hazardous to Health (COSHH) Regulations 2002 guidelines. A well-ventilated area is likely to be a prerequisite.

If any flesh or fat remains on or in the bones, the collection will be susceptible to insect and mold damage and will degrade. Fluctuations in temperature and humidity can also damage bone. Ideally, clean, dry bones should be stored in a controlled environment, with some ventilation. If stored in plastic bags, the bags should be perforated. Depending on the preparation method used, the bones may become unsuitable for future DNA analysis.

Invertebrates

Accurate identification of, for example, mollusc and insect species from the fresh specimen using relevant identification keys is vital before they are processed. A risk analysis of all processes and chemicals used should be carried out. Insect and mollusc collections can comprise many small specimens, which need to be stored in suitable boxes and trays so that they are easily accessible but protected from rough handling and light. The storage environment should be controlled to provide some ventilation and avoid fluctuations in temperature and humidity.

Insects can be pinned or mounted on microscope slides, depending on their size. Insects, and many other biological reference materials, can also be preserved in fluid, but such specimens are not as easy to use as comparanda because they cannot be readily handled. Some chemicals used to relax insects for pinning or mounting them on slides may destroy DNA. Insect collections are prone to insect attack, while mollusc collections

can be affected by acidic fumes released from organic packing material. Molluscs can be stored dry in sealed plastic bags.

Organization and cataloging

There are three ways to organize a reference collection: in an evolutionary sequence, placing related taxa close to each other; in an alphabetical system, requiring no specialist knowledge to locate taxa; or in an index collection, arranged by element and size. The choice of sequence is not always simple and advice should be sought from other laboratories or taxonomists. It is important that the correct biological nomenclature is used; this may be based on a national checklist or on an online resource such as the GBIF Backbone Taxonomy (GBIF Secretariat 2016).

A catalog of the collection, usually in the form of a database, should indicate where to find a specimen and comprehensive details of the specimen's provenance, including, for example, source location/habitat, age, life history, and cause of death. The set of fields will usually be similar to that in the Access to Biological Collections Data (ABCD) schema (TDWG Task Group 2007). The data should be atomized, for example, scientific names broken down into genus, species, and author fields, locality and country recorded separately. It is better to have a smaller number of fields that are consistently filled, than many fields that are mostly empty. Once provenance data have been added to a database, the original documentation (including permits) should be stored safely.

When specimens are integrated into a collection, they need to be given a unique accession number. In skeletal collections, that number can be written on each element; for pinned insects, the number is written on a card label; the number can also be written on the bag or container housing the specimen. If previously held elsewhere, the original collector and collection accession number should be retained, and it is good practice to cite both in reports.

SEE ALSO: Archaeoentomology; Charcoal and Wood Analysis; Environmental Archaeology; Paleoethnobotany; Zooarchaeology

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Vegetation Modeling Using Pollen Data

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Palynology (see PALYNOLOGY) is one of the most commonly used methods of reconstructing the environmental context (see ENVIRONMENT AND LANDSCAPE and PALEOENVIRONMENTAL RECONSTRUCTION) of archaeological sites. Traditional interpretations of pollen records collected within archaeological landscapes have taken a broadly narrative approach, with pollen diagrams being interpreted in the form of descriptions of successive patterns of land-cover at different points in time, drawing on knowledge of plant ecology (both of individual species and of habitats such as woodland) and of land-cover types created by different human activities, with little attempt made to assess the uncertainty of the reconstruction or to use a formal hypothesis testing (see HYPOTHESIS TESTING) approach. These descriptive reconstructions provide background for archaeological interpretation (see INTERPRETATION), but are too general to be fully integrated into most reconstructions or analyses. To address this gap, pollen data need to be translated into quantitative estimates of past vegetation abundance or change and/or maps of past land-cover.

This has been an important goal for the palynological community since its earliest days. Several different approaches to this translation process have been developed, which can be grouped into two categories: those based on the characteristics of the whole pollen assemblage, and those using an algebraic model of the relationship between individual pollen types and the plants that produced the pollen. Examples of whole-assemblage techniques include the modern analog technique (MAT: Overpeck, Webb, and Prentice 1985), biomization (Prentice et al.

1996), and pseudobiomization (Fyfe, Roberts, and Woodbridge 2010). The MAT compares modern pollen assemblages with those from subfossil samples, on the assumption that modern vegetation communities which produce pollen assemblages that are statistically similar to the subfossil assemblages are good analogs for the past environment that produced them. However, the MAT can only reconstruct landscapes that have extant analogs, and many past landscapes have no modern analog—for example, the steppe and tundra vegetation in lowland Europe during the Late Glacial, or landscapes with large populations of wild mega-herbivores like aurochs. In the biomization approach, pollen taxa are assigned to one or more plant functional types (PFTs), which are broad classes defined by characteristics such as plant life form, leaf type, phenology, and climatic adaptations, and then the spectrum of PFTs present is used to assign samples (and therefore the environments in which they formed) to large-scale biomes. However, many pollen taxa can be assigned to more than one PFT, since one pollen taxon is typically made up of pollen from several different plant species with differing ecological requirements, and the reconstructions produced apply spatially at a subcontinental or continental scale, too coarse for most archaeological research questions. Pseudobiomization addresses the second problem by assigning pollen taxa to land-cover classes (LCCs) rather than PFTs, allowing inclusion of anthropogenically modified vegetation types such as pastoral or arable land, and producing reconstructions at a regional or landscape scale. However, pollen taxa cannot be assigned unambiguously to LCCs, and the first problem remains.

The second approach uses algebraic models of the relationship between plant abundance in the landscape and the pollen assemblage. Interpretation of pollen assemblages is complicated not just by taxonomic imprecision, but also because different plant species produce different amounts of pollen and exploit different pollen dispersal mechanisms, and because different sizes and types of sampling site (e.g., small lakes (see LAKE DEPOSITS); large mires (see PEAT DEPOSITS))

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record the landscape with different levels of spatial sensitivity. Taxon-specific models allow these differences to be explicitly acknowledged and allowed for in the results. Most such models are linear (see *LINEAR MODELS*), although recent advances in computing power and spatial analysis are opening up a wider range of options. These models have multiple underpinning assumptions, and need to be calibrated for each pollen taxon of interest; so far, calibration datasets mostly exist for temperate ecosystems (see *TEMPERATE ENVIRONMENTS*).

The most widely used linear model (see *LINEAR MODELS*) is termed the Prentice-Sugita model (Prentice 1985), and it underlies two different process-based modeling approaches to quantitative vegetation reconstruction that are currently being actively applied: the landscape reconstruction algorithm (LRA: Sugita 2007a,b) and the multiple scenario approach (MSA: Bunting and Middleton 2009). The LRA uses an algebraic approach to reconstruction. First, pollen records from large lakes (>500 ha) are used to reconstruct the regional vegetation (within c. 100 km radius of the lake). These values are then used to calculate the pollen contribution from the regional vegetation (the “background” pollen rain) to the pollen assemblage forming in a smaller sedimentary basin (typically <10 ha), and separate that from the pollen component from the local vegetation within c. 100–3000 m of the basin, which can then be reconstructed. A significant advantage of the LRA is that a formal estimate of the spatial scale of the reconstruction is included in the output of the model, but the reconstructed vegetation abundance is expressed in terms of distance-weighted plant abundance rather than actual land-cover, and no information on the spatial arrangement of the different vegetation communities is obtained. This approach has been successfully validated against present-day datasets where both pollen and vegetation data can be measured directly, and actual vegetation can be compared with reconstructions, and applications have so far tended to focus on large-scale vegetation reconstructions addressing questions of landscape openness and changing land-cover across subcontinental scale areas.

The MSA uses an iterative approach to reconstruction. A geographical information system (GIS) is used to combine knowledge of past

environmental constraints such as topography and geology with simple ecological principles to generate possible land-cover maps for a specific area around one or more pollen sample locations. Many thousands of hypothetical land-cover maps can be generated by varying the range of values for the distribution of each community (for example, placing treelines at different altitudes, or varying sea-level for coastal communities) and randomly placing patches of vegetation communities into suitable locations in different proportions. The Prentice-Sugita model is used to simulate the pollen assemblage at each of the sampling locations for each possible land-cover map, and these pollen assemblages are then compared with the actual assemblages recorded using the same statistical approach as the MAT. Where actual and simulated assemblages are statistically very similar, the possible land-cover map is considered to be a “modeled analog” of the past landscape. One strength of this approach is that it can identify equifinal solutions, situations where ecologically distinct land-cover arrangements can produce statistically indistinguishable pollen assemblages, which can then form a basis for future hypothesis testing (see *HYPOTHESIS TESTING*).

An intermediate approach takes a limited number of simplified possible past land-cover maps and uses the Prentice-Sugita model to simulate pollen assemblages for comparison with subfossil records. This multiple hypothesis testing (see *HYPOTHESIS TESTING*) framework allows better understanding of the responsiveness of the pollen signal to changes in land-cover arrangement (e.g., Tipping et al. 2009), and can be an effective means of exploring whether pollen analytical methods can actually be used to test archaeologically derived hypotheses of past landscape organization, or to inform or underpin reconstructions used for education and outreach (see *HERITAGE INTERPRETATION*), such as artists’ reconstructions and virtual reality modeling (see *VIRTUAL REALITY MODELING*). The technology used to produce digital reconstructions is often so sophisticated that they may be uncritically accepted as being scientifically accurate, and pollen-based hypothesis testing may offer a useful method for improving the quality of the input information.

Both the LRA and the MSA are best used with pollen records from multiple sites, which require robust chronologies to ensure that age-equivalent pollen assemblages are compared, and are limited by the assumptions and model-calibration needs of the Prentice-Sugita model. A key issue concerns the measure of the amount of pollen produced by different plants, or relative pollen productivity (RPP). To date, most published RPP estimates are from northern Europe and North America, although some values are available for sites in Africa and Asia, and research is currently underway to extend this coverage. Both approaches effectively assume that RPP is a constant within a geographical region, both in time and space, and therefore that changes in pollen proportions through a sediment core are entirely produced by changes in the abundance or position of vegetation around the sampled sedimentary basin. However, a review of published RPP estimates across northern Europe showed that estimates were highly variable (Broström et al. 2008); this may reflect real differences in RPP related to climate or land management (e.g., in a pasture, grasses flower less profusely than in a hay meadow, and therefore the amount of pollen produced will vary markedly even though both systems are dominated by grasses), or be an artifact of differing methodologies or small datasets, since vegetation survey for such studies as currently practiced is highly labor-intensive.

Pollen-based reconstructions of past land-cover can be used as the basis for future research, especially within a hypothesis testing (see HYPOTHESIS TESTING) framework. Drawing on multidisciplinary datasets from both on-site and off-site contexts using a wide range of proxies for past environments such as insect remains (see ARCHAEOENTOMOLOGY), molluscs (see LAND AND FRESHWATER MOLLUSCS) and plant macrofossils (see PALEOETHNOBOTANY) can both add detail to the reconstructed landscape and enable the analyst to distinguish between alternatives that cannot be separated using pollen data alone. Landscape archaeological research can also be used to construct or test hypotheses of land-cover organization, and to constrain pollen-based reconstructions.

As computing power and speed increases, alternative approaches to studying past vegetation cover become possible. Dynamic vegetation

models such as LPJ-GUESS or FORMOD incorporate a range of plant physiological processes to model how vegetation communities may change in response to changes in parameters such as climate or atmospheric carbon dioxide levels, and these models have been applied to attempt reconstructions of possible past vegetation over archaeologically relevant timescales. Testing the outputs of such models against pollen data is rarely done, and the modeling approaches discussed here may offer new opportunities to bring together the sophisticated modeling of plant ecological research with environmental archaeology (see ENVIRONMENTAL ARCHAEOLOGY), to the benefit of both.

SEE ALSO: Hypothesis Testing; Linear Models; Paleoenvironmental Reconstruction; Palynology; Virtual Reality Modeling

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Water Pollution

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Water pollution is arguably one of the most significant issues that has faced humanity over the ages because it adversely affects the health of billions of people globally, leading to diseases such as cholera, diarrhea, and cancer. Water systems, for example, have been polluted with human waste for millennia, causing cholera outbreaks and pandemics that have killed millions of people (Morris 2011). The mining of metal-bearing ores has contaminated water systems and caused extensive human lead and mercury poisoning (Pyatt et al. 2005; Robins 2011). Water pollution has also affected the health of ecosystems, causing changes in diversity, population density, disease, and death (Neto et al. 2016).

Water can be polluted by metals and metalloids such as arsenic, cadmium, lead, and mercury, by organic compounds such as manure or sewage, by radionuclides (radioactive isotopes; see ISOTOPES) such as cesium-137 and uranium-138, by nutrients such as phosphate and nitrate, and by acids or bases. These elements and compounds occur naturally in low to high concentrations in waters due to the weathering of rocks and soils and the decomposition of organic materials. They can be added to rivers, lakes, glaciers, the atmosphere, groundwaters, and oceans by natural events such as volcanic eruptions, floods, and landslides. Alternatively, anthropogenic activities such as mining, agriculture, manufacturing, and urbanization can pollute waters through runoff, accidental spills, seepages from cesspools, or from mine wastes. Some of these anthropogenic activities, especially those related to inadequate water purification, can also result in the pollution of water by pathogens such as *Escherichia coli* and cholera, or by heat, forming thermal pollution.

Pollutants enter water systems from “point sources” or “diffuse sources.” Point sources are single discharge positions, and examples include mine adits, sewage outlets, and latrines. Diffuse sources are those with multiple discharge positions. These include leaching of mine waste piles, atmospheric fallout, flooding, and agricultural runoff. In Ireland, for example, carbon and nitrogen isotope geochemistry of lake sediments, along with pollen and charcoal analysis, has been used to show that Neolithic and Bronze Age farming caused changes in chironomid subfossil community compositions (Taylor et al. 2017). Another example of diffuse pollution is that of mining-contaminated rivers. The channel and floodplain sediment of these systems has been enriched in metals such as lead, zinc, and cadmium through the ejection, in some cases over hundreds to thousands of years, of mine waste material into river systems (see RIVER SYSTEMS). These sediments act as a diffuse source of metals to waters through physical and biogeochemical weathering, and this is often a more significant pollutant source than the weathering of mine waste tips that line the rivers (Macklin et al. 2006).

Because ancient waters are rarely preserved, the unraveling of the historical effects of water pollution involves the use of “environmental proxies,” preserved physical, geochemical, and biological materials within the geologic record that can be analyzed and dated to reconstruct past conditions (USGS 2017). Current research on historical water pollution focuses on determining its effects on past populations and on using and developing such environmental proxies for studying water quality. In many cases, sediment cores (see CORING) are used for these studies, because they provide a temporal record extending back tens to hundreds or thousands of years and contain proxies such as foraminifera, diatoms, and pollen, while the sequence of deposits can be analyzed for their geochemical signatures that in turn give direct information about water pollutants. For example, Neto et al. (2016) collected

sedimentological, foraminifera, pollen, and geochemical data for the last 5,000 years from cored sediments from Guanabara Bay, Brazil, and defined three stages of environmental history in the area. The most recent stage, occurring in the last few hundred years, was characterized by metal pollution (lead, nickel, copper, chromium, zinc, manganese) that leads to vegetation change and environmental deterioration. Nitrogen and carbon isotopic and trace metal geochemical data from sediment cores were used to demonstrate that Xing Yun Lake in Yunnan Province, China, was polluted as far back as 500 CE (Hilman et al. 2014). The taxonomy and morphological changes in diatoms (see DIATOMS) in a sediment core from Lac Dufault, Abitibi, Canada, were shown to shift and progressively deform, respectively, due to water metal pollution arising from mining (Cattaneo et al. 2004). Parasites (see PARASITE OVA AND CYSTS) found in latrine and cesspool sediments from the Middle East have confirmed cases of dysentery in Jerusalem in the Middle Ages (Mitchell, Stern, and Tepper 2008).

Future research on past water pollution will continue to determine its spatial extent and effects on humans and ecosystems. To achieve this, the physical, geochemical, and biological proxies developed to date will continue to be used, and these will be improved and augmented by new techniques. For example, ancient DNA has recently been profiled from a nineteenth-century cholera intestinal specimen and a medieval Black Death plague victim's tooth using a microarray detection technique. This technique has been proposed to be a rapid and inexpensive screening tool for similar archaeological samples (Devault et al. 2014). The exposure of people living in the Atacama Desert in Chile from 500–1450 CE to naturally occurring arsenic has been assessed using synchrotron radiation (Kakoulli et al. 2014). High concentrations of inorganic arsenic have been found in hair samples, suggesting chronic uptake of the element from polluted waters. Because synchrotron radiation has much higher intensity than that generated conventionally, it can be used for very small samples with low elemental concentrations, and therefore has great applicability for archaeological studies of water pollution.

SEE ALSO: Air Pollution; Sampling in Environmental Studies; Urban Environments

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Wheat

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Cereals account for more than 50 percent of worldwide crop production and are important renewable resources for food, feed, and industrial materials. Wheat is the primary cereal of temperate regions and the staple food for about 40 percent of the world's population. It is commonly recognized as a grass, as a kernel of wheat is the caryopsis or fruit of a plant of the genus *Triticum* from the grass family (Poaceae).

Wheat provided the agronomic basis for development of the earliest groups in Mesopotamia, and has been found at archaeological sites in the region dating back to 12,000 BP. The spread of wheat from its site of origin across the world has been elegantly described by several researchers and is only summarized here. The main route into Europe was via Anatolia to Greece (8000 BP) and then both northwards through the Balkans to the Danube (7000 BP) and across to Italy, France, and Spain (7000 BP), finally reaching the United Kingdom and Scandinavia by about 6000 BP. Similarly, wheat spread via Iran into central Asia, reaching China by about 3000 BP, and to Africa, initially via Egypt. It was introduced by the Spaniards to Mexico in 1529 and to Australia in 1788 (Abbo et al. 2013). Nowadays, wheat is grown on every arable continent, and it is the most important food for people living in temperate regions of the world.

The most important wheats are: bread (*Triticum aestivum*), used to make bread; durum (*T. durum*), used to make pasta, couscous, and bulgur; and club (*T. compactum*), used to make softer cakes, crackers, cookies, and pastries. Additionally, some wheat is used by industry for the production of starch, malt, and other products. Small amounts of other wheat species

(einkorn, emmer, spelt) are still grown in some regions including Spain, Turkey, the Balkans, and the Indian subcontinent, while spelt continues to be grown in Europe, particularly in Alpine areas (Kilian et al. 2009).

Nearly a century ago, it was determined that the cultivated wheat species of the genus *Triticum* have chromosome numbers of $2n = 14$, 28, and 42. This indicated that the basic Triticeae genome is organized into seven chromosomes ($x = 7$) and the various *Triticum* species consist of diploids ($2n = 2x = 14$), tetraploids ($2n = 4x = 28$), and hexaploids ($2n = 6x = 42$) (Faris 2013). The first wheat to be cultivated successfully was einkorn (*T. monococcum*), a diploid species ($2n = 2x = 14$, $A^m A^m$). The site of domesticated einkorn wheat, according to genetics and archaeological studies, is found in the Karacadağ mountain region of Diyarbakır, Turkey. Although einkorn was important for Neolithic agriculture, today it is a relic crop and is rarely grown (Heun et al. 1997). A further important step in the evolution of wheats was the domestication of emmer, which is a tetraploid wheat ($2n = 28$), from its wild progenitor *T. dicoccoides*. Wild emmer, an AABB wheat, with its A genome derived from *T. urartu* and its B genome probably derived from the S genome present in the *Sitopsis* section of *Aegilops*, with *Ae. speltoides* being the closest extant species, has brittle ears that shatter at maturity into spikelets that bear relatively large grains. Unlike their wild progenitor, all domesticated tetraploid wheats have a nonbrittle rachis, which is more amenable to harvest as the ears do not fall apart. Domesticated emmer wheat, *T. dicoccum*, has hulled grain and the AABB genome that is common to other domesticated tetraploid wheats (Faris 2013). Emmer was first cultivated in the southern Levant (Netiv Higdud, Tell Aswad, other PPNA sites), while einkorn is found in northern Pre-Pottery Neolithic A (PPNA) sites (Abu Hureyra, Mureybet, Jerf el Ahmar, Göbekli Tepe, other southern PPNA) (Özkan et al. 2010).

The wheat species with tetraploid genomes were subsequently involved in accidental

crosses with a wild diploid species (*Aegilops tauschii*), giving rise to hexaploid wheats. Domesticated hexaploid wheats have no wild hexaploid progenitor in nature; it is, therefore, a farming-associated natural hybrid that has since become the world's leading crop. The appearance of the free-threshing phenotype can be illustrated with the comparative genetics of two hexaploid wheat varieties, *T. spelta* (spelt wheat) and *T. aestivum* (bread wheat, a free-threshing form). Both *T. spelta* and *T. aestivum* have an AABBDD hexaploid genome (Kilian et al. 2009).

The main difference between the wild forms of wheat and domesticated wheat is that domesticated forms have a nonshattering rachis. When wild wheat is ripe, the rachis—the stem that keeps the wheat ear together—shatters so that the seeds can disperse themselves. This is clearly an important trait for ensuring seed dispersal in natural populations, but meant that the ears broke up when harvested by people using cutting tools or plucking by hand. Plants with a non-shattering rachis, determined by mutations at the *Br1* (brittle rachis) locus, were preferentially selected as a result of these harvesting techniques, leading to the fixing of this trait in domesticated wheats. The second important trait found in domesticated wheats is the change from hulled forms, in which the glumes adhere tightly to the grain, to free-threshing (naked) forms, where the grain is held loosely within its chaff. The free-threshing forms are caused by a dominant mutant at the *Q* locus, which modifies the effects of recessive mutations at the *Tg* (tenacious glume) locus. The early-domesticated forms of einkorn, emmer, and spelt are all hulled, whereas modern forms of tetraploid and hexaploid wheats are free-threshing (Faris 2013).

Together with diploid and tetraploid species, free-threshing hexaploid wheat has been identified in the settlements of Abu Hureyra 2A, Cafer Höyük, Çayönü, Tell Aswad II, Aşıklıhöyük, Ghorraife, and Tell Halula within the so-called Fertile Crescent, which is located in the Middle East and encompasses a region extending from Jordan, Israel, Lebanon, and Syria through southeast Turkey and along the Tigris and Euphrates rivers through Iraq and western Iran. *Triticum monococcum* and *T. dicoccum* have also been identified in all the settlements in the Near East,

but hexaploid species such as *T. aestivum* Host and *T. spelta* have not.

Compared to the diploid and tetraploid species, the origin and spread of the hexaploid species is poorly understood. The genetic data indicate that hulled hexaploid wheat species are more “primitive” than free-threshing hexaploid wheat species. However, contrary to the genetic data, the oldest findings in archaeological record are of free-threshing hexaploid species.

The distribution of *Ae. tauschii*, the source of the D genome in the principal hexaploid wheats, covers a very large area, from northeastern Anatolia to Armenia, Azerbaijan, the coast of the Caspian Sea, Pakistan, Afghanistan, and the northeastern part of Kyrgyzstan. The range of *Ae. tauschii* hints at its adaptation to various climatic and environmental conditions: from the desert-like environment of the mountain foothills of Afghanistan to the mild climate of the Caspian Sea coast. Furthermore, the identification of this species in northeastern Anatolia, where continental climate conditions and steppe plant cover prevail, but not around the Karacadağ region, where the wild progenitors of *T. dicoccum* and *T. monococcum* have been identified, seems like a remarkable contradiction—especially as some researchers attribute the adaptation of *T. spelta* to mild humid or harsh continental climate conditions as due to the incorporation of the *Ae. tauschii* genome.

However, the identification of *Ae. tauschii* around Şanlıurfa, where Çayönü, Nevalı Çori, and Göbekli Tepe settlements were located, suggests that the natural geographical range of *Ae. tauschii* extended into this region in the past and that *T. spelta* may have first been grown in settlements in the foothills of Karacadağ. Indeed, *T. aestivum* ssp. *compactum* has been identified in Can Hasan III, *T. aestivum/durum* in Çayönü, and rachises of bread wheat in Caferhöyük III and IV levels (Zohary, Hopf, and Weiss 2000).

The question of the geographic origin of wheat domestication has been the subject of much research. Recently, based on archaeological, archaeobotanical, and genetic evidence, a well-defined “core area” hypothesis was suggested. The core area hypothesis maintains that the Near Eastern Neolithic crop package, including both cereals and legumes, was domesticated within a relatively restricted area in southeastern

Turkey once or a very limited number of times; that is, there was monophyletic domestication (Abbo, Lev-Yadun, and Gopher 2012; Abbo et al. 2013). An alternative hypothesis favors a geographically diffused Near Eastern wheat domestication pattern, comprising a series of separate events in which wheats were domesticated through a sequence of genetically and culturally independent occurrences. The debate concerning “core area” versus diffused domestication is still part of the discussion on Near Eastern plant domestication (Fuller, Willcox, and Allaby 2011). Therefore, there is still much work needed to understand plant domestication models, particularly for wheat domestication.

The *Triticum new glume wheat* type

The recent study of vegetal macroscopic plant remains from Anatolia once again shows the strategic role of the region in the origin of wheat domestication. Archaeobotanical investigations have shown that the *Triticum new glume wheat* type, a type of wheat that has only been identified archaeologically as macroscopic plant remains (Jones, Valamoti, and Charles 2000), has been used since the ninth millennium BCE. The earliest records so far come from the following Anatolian sites: Pre-Pottery Neolithic B (PPNB) Caferhöyük, Pottery Neolithic (PN) Çatalhöyük, PN Yumuktepe, and PN Yenikapı.

The identification of *Triticum new glume wheat* type is rather complex, because the caryopsis does not always allow precise identification. For this reason, researchers mostly use glume bases for taxonomical resolution. Identification is possible through the analysis of the fork's morphology, especially through the wide and deep scar left by the disarticulation of rachis. This taxon, according to some authors, belongs to the tetraploid group. Among the possible tetraploid cereals that the *Triticum new glume wheat* type might have sprung from are wild species like *T. diccoides* and *T. timopheevi* ssp. *araraticum*.

Although the analyses carried out so far have enabled the proposition of several theories on the taxonomical origin of *Triticum new glume wheat* type, they have not been able to entirely clarify the other problems regarding this species

(origin, diffusion, etc.) Therefore, more reliable archaeobotanical data and analytical tools are required in order to propose more precise theses regarding the taxonomical origin of this problematic species.

Current knowledge of wheat domestication is largely derived from morphological analysis of archaeobotanical remains and population genetic analysis of present-day samples. However, with the advent of ancient DNA analysis, in particular next generation sequencing (NGS), it is possible to carry out analysis of charred cereal grain, allowing the stages of wheat domestication to be presented in dimensions of time and space, including the genetic make-up of *Triticum new glume wheat* type.

SEE ALSO: Barley, Rye, and Oats; Domestication; Paleoethnobotany; Paleoethnobotany and Ancient DNA Analysis

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Zooarchaeology

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Zooarchaeology is the discipline of archaeological science that seeks to understand past interactions between people and other animals through investigation of the archaeological record. The term *archaeozoology* is also used, particularly in Europe: The two terms are effectively synonymous. The principal study materials for zooarchaeology are the physical remains of animals themselves; hence the research literature mostly presents studies of bones and marine shells (see MARINE MOLLUSCS). However, other forms of evidence are pertinent, such as tracks and trails, enclosures and droveways, skin, hair, and feces (see COPROLITES), and bone and shell artifacts. The use of insect (see ARCHAEOENTOMOLOGY) and nonmarine mollusc (see LAND AND FRESHWATER MOLLUSCS) remains as paleoenvironmental evidence could also be subsumed under zooarchaeology, but are generally regarded as separate disciplines. Zooarchaeology uses essentially the same working methods as paleontology—systematic identification of specimens, analysis of depositional context, and inference of individual and population health and behavior—with the important difference that human interaction with the animals is at the center of the study, hence the focus on vertebrate and large invertebrate animals that have been hunted, farmed, or foraged. When investigating animal remains from early hominin sites, the differentiation of zooarchaeology and paleontology is more problematic, especially when dealing with animal species that are now extinct.

The earliest instances of people wondering about ancient animal bones and shells are lost in prehistory, though examples of the apparent curation of old bones are occasionally recognized in the archaeological record. The systematic study of excavated animal remains for what they show of past human entanglements with animals is

at least as old as archaeology itself. From the mid-nineteenth century onwards, antiquarianism developed into archaeology under the twin influences of evolutionism and positivism (see POSITIVISM) and the development of zooarchaeology was part of that process. A key project was Ludwig Rütimeyer's pioneering study of animal bones from the "lake-village" sites of Switzerland (Rütimeyer 1861) in which he sought to understand the bones both as evidence of the economy of the settlement sites and of the natural history of their region. In particular, Rütimeyer tried to differentiate bones of wild and domesticated forms of the same species, such as pigs and wild boars, anticipating a major theme of later zooarchaeological research (see PIGS). Meanwhile, work had begun in Denmark to systematically investigate bones and shells from the many large prehistoric middens (Køkkenmøddinger) in that country (Andersen 2000). Other shell and bone middens attracted attention. Some of the earliest zooarchaeological work undertaken in North America was carried out by William Dall (1877) during his pioneering investigation of archaeology and ethnology in the Aleutian Islands and Alaska. On the Atlantic coast, sporadic work on shell middens in Maine began around the same time. Writing in 1912, Thomas Joyce gave the first published account of the huge *sambaqui* middens of coastal Brazil, comparing them with the Danish middens. Most of these early midden investigations used bones and shells as evidence of foraging and diet. In Paleolithic sites in Europe, based more on Pleistocene deposits in caves, large mammals were used as biostratigraphic markers in floating chronologies (see QUATERNARY LARGE-MAMMAL ZONES). Differentiation of a "Mammoth Age" from a "Reindeer Age" was crude, but it at least recognized the value of excavated bones as indicators of environmentally driven regional changes of biota and allowed some regional stratigraphic frameworks to be proposed.

Zooarchaeology in Europe and North America thus has its roots in the 1860s and 1870s. Despite that early start, and with a few notable exceptions, adoption of the systematic study

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of excavated bones and shells was slow and piecemeal until well into the twentieth century. The procedures that underpin zooarchaeology today were largely developed in the second half of the twentieth century as zooarchaeology moved away from paleontology, in particular through the use of ethnographic analogy (see ETHNOARCHAEOLOGY) to propose that social and economic aspects of food sharing and economic behavior could be inferred from excavated bone assemblages. Theodore White's observations of bone deposition by Native Americans continue to be influential, as does the work of Lewis Binford in Arctic North America and of Bob Brain in southern Africa (Lyman 1994). One criticism that is directed at this phase in zooarchaeology's development is that it assumed that past peoples behaved rationally and optimally in their selection of prey and utilization of carcasses, despite some ethnographic evidence that this is not always the case. The emergence of social zooarchaeology in the 2000s can be seen as a reaction to those normative assumptions (Russell 2012). The 1960–1970s saw zooarchaeology extend into Central and South America, and especially in southwest Asia, followed in subsequent decades by important research in East and Southeast Asia and Australasia. At the time of writing, sub-Saharan Africa stands out for its undeveloped potential for zooarchaeology, despite excellent work by a few individuals.

Although the research agenda of zooarchaeology differs from project to project, certain techniques of data acquisition have dominated the development of the discipline. Taphonomy (see TAPHONOMY), the analysis of assemblage deposition and diagenesis, has been the elephant in zooarchaeology's closet ever since Rüttimeyer's pioneering work. Paleontologists have understood the importance of taphonomy for many decades. Weigelt studied the postmortem degradation and weathering of animal carcasses in the 1920s, and Efremov introduced the term "taphonomy" to paleontology in 1940. As early as 1938, Pei Wen-Chung undertook a pioneering analysis of breakage patterns and cut and tooth marks on bones from Paleolithic sites in China, seeking to differentiate traces of human activity from the action of scavengers and erosion. The Paleolithic continued to be the main focus for taphonomic studies in zooarchaeology, reflecting

the considerable overlap between paleontology and Pleistocene zooarchaeology (Shipman 1981). Although textbooks conventionally discuss taphonomy, often presenting "flow diagrams" of the various filters that stand between the researcher and the ancient animals, analysis of the depositional history of zooarchaeological assemblages has yet to become a standard element of every project. Even where assemblage taphonomy is discussed, the emphasis tends to be on the loss of information rather than on using the taphonomic evidence in order to gain information about deposit formation. The work of Lee Lyman (1994) has done much to bring the potential of taphonomic analysis to zooarchaeology's attention.

The techniques of taphonomic analysis are essentially those of good observation: differentiating fractures that occurred when the bone was "fresh" or already weathered, recognizing subaerial erosion and weathering, distinguishing purposeful cut marks from chance abrasions, identifying the species responsible for tooth marks and gnawing damage. The interpretation of cut marks from butchery is particularly complex. They integrate the musculoskeletal anatomy of the animal carcass, the custom of the people concerned, and the competence and habits of the individual butcher. Diagenetic change in bone is highly complex and context-specific, though changes in nano- to microscale porosity are clearly significant. Bone is a composite of a mineral phase (bioapatite) and an organic phase (collagen), each of which conveys some protection from chemical alteration to the other phase. Diagenetic questions relating to shell middens are somewhat simpler than for bone, as mollusc shells are essentially calcium carbonate in varying proportions of calcite and aragonite. Although generalizations can be made up to a point, such as that bone and shell will be more likely to survive burial in neutral to alkaline deposits than in acidic sediments, context-specific conditions may vary over very short distances. The presence of shells, for example, may raise local pH and so protect bone in the same deposit, or the shells may, by opening the texture and therefore drainage of the deposit, accelerate bone deterioration through water and air permeation. Food debris deposits that include quantities of bone, shell, and ash may be geochemically highly distinctive, with

unexpected consequences for the deterioration of different materials.

Identification is perhaps the most basic yet challenging procedure in zooarchaeology. A typical excavated bone or shell assemblage combines fragments from an unknown number of individuals of unknown species. The identification categories used in zooarchaeology do not always directly equate to Linnaean species names, and the term “taxa” is preferable. Taxa such as “sheep/goat” or “medium venerid” are used of necessity where differentiation to a more precise level is not possible or justifiable. Identification of bones proceeds by recognition of the skeletal element, based on a knowledge of the tetrapod skeleton, then attempts to attribute the specimen to as low a taxonomic level as the observable details of the specimen will allow. Obviously this depends on the experience and rigor of the researcher concerned and their access to good comparative collections of modern specimens (see *USE OF BIOLOGICAL COLLECTIONS*), so there are significant issues around validity and quality control. One particular problem is the temptation to ascribe a specimen to a particular species because it is thought to be the most likely to occur at that time and place, rather than because of specific anatomical criteria. Biometric techniques may allow differentiation of some groups of closely related taxa, or at least indicate the probability that more than one species is present. Biomolecular analytical methods that can distinguish variations of protein and DNA chemistry (see *ZOOARCHAEOLOGY AND ANCIENT DNA*) provide a means of “cross-checking” the identification of key specimens. These laboratory methods are not applicable to every fragment in a large assemblage, but have proved their worth in identifying the raw material source in bone and shell artifacts (e.g., see Demarchi et al. 2014 for shell; Welker et al. 2015 for bone).

The measurement of animal bones has had a revered place in zooarchaeology since the late nineteenth century, when Pitt-Rivers compared measurements of prehistoric sheep from southern England to those of extant “primitive” breeds. The rationale for acquiring biometric data is not always clearly stated but is generally to allow either quantified sample-to-sample comparison of a given species, testing for significant intersample differences, or analysis of

within-sample variation, often in the hope of identifying males, females, and (in domesticates) male castrates. The domestication of livestock was often accompanied by size changes, and simple biometric comparisons are often used to differentiate, for example, domestic pig from wild boar or domestic cattle from aurochs. The data are usually simple linear measures between anatomical landmarks, following a set of standards such as those published by von den Driesch (1976). Analysis generally begins with univariate bar graphs to explore size variation, and bivariate scattergrams to investigate covariation of size and proportion, for example in lengths and breadths of a skeletal element. The fragmentation of archaeological bones means that even a large assemblage will yield relatively few measurable specimens of any one element. To maximize data utility, a range of size-scaling methods have been used, in particular a log-ratio technique based on methods developed by paleontologist G. G. Simpson. These size-scaling methods convert each observed measurement to a ratio of a standard individual or sample, allowing direct comparison of measurements taken on different parts of the skeleton. Similar challenges arise with shells. Assessment of the size range may be informative regarding harvesting strategies and subsistence yield, but breakage of shells makes such assessment difficult, necessitating means of reconstructing overall size from surviving fragments.

Multivariate analyses (see *MULTIVARIATE ANALYSIS*) of size and shape are mostly applied to bones and teeth, and tend to be eigenvector-based, such as the use of principal components analysis to explore the maximum differentiation between samples of different provenance, or of discriminant function analysis to examine the distribution of “unknown” archaeological specimens against “known” groups such as closely related taxa. These techniques are increasingly replaced by more subtle analysis of shape as captured by geometric morphometric techniques (GMM) (see *GEOMETRIC MORPHOMETRICS*). Based on the analysis of “clouds” of landmark points in multidimensional space, GMM techniques allow complex analysis of shapes that are difficult to parameterize using conventional biometry, in particular teeth.

Investigation of the animal bone record has focused on the phenotype, as proxy evidence of the genotype. Analysis of ancient DNA (aDNA) recovered from bone allows a more direct approach, using both ancient and modern biomolecular evidence to assess population movements and changes. The impact of aDNA has been to make it possible to ask questions that would once have seemed unanswerable and therefore pointless, in particular questions regarding intraspecies variation and the recognition of regional demes (Brown and Brown 2011). This has allowed detailed questions to be asked about, for example, the spread of domesticates from their source populations into new regions. Although aDNA analysis initially suffered reputational damage from high cost and modern contamination, next generation sequencing (see DNA: NEXT GENERATION SEQUENCING) has reduced the cost and enhanced the sensitivity by orders of magnitude, and the challenge for zooarchaeology today is how to manage the huge volumes of data produced by aDNA laboratories. Further developments have included the identification of animal DNA in sediment sequences, allowing species to be placed in time and space in the absence of their bones, and recovery of DNA from dated parchments, giving precisely dated genomic data for (mainly) cattle and sheep. To date, there has been little success in aDNA analysis from mollusc shells, although DNA-based identification of ancient avian egg-shell has been successful.

The study of mortality profiles is central to zooarchaeology, as it reflects human decision making in hunting strategies or in the management of domestic herds and flocks. The age of vertebrate animals at death is usually estimated by combining the state of eruption and attrition of the teeth and the state of fusion (i.e., maturity) of limb elements. Dental analysis is generally regarded as being the more precise and more reliable, as post-cranial growth and maturation can be subject to environmental effects such as undernutrition and the castration of males. Influential early work on the interpretation of domestic mammal mortality proposed idealized culling models for sheep and goats on the basis that husbandry would target meat, milk, or wool production. These models have been widely applied, often in cultural contexts quite

different to those for which they were developed, and have been criticized for being improbably normative and insufficiently case-contingent. As elsewhere in zooarchaeology, the assumption of rational, economically optimizing behavior on the part of livestock keepers may be misleading, and early models were simplistic in their allowance for risk mitigation. Many prey and domestic animals breed in a predictable season, so precise knowledge of age at death can yield information about seasonal activity. If bison can be expected to have given birth in the spring, then an excavated assemblage that includes animals of around 8 months, 20 months, and 32 months of age, but none of around 12–16 months, probably represents a winter kill. Seasonal analysis is most straightforward in the case of coastal birds (see BIRDS), which may only be accessible during the nesting season, when immature bones may comprise much of the zooarchaeological record (Serjeantson 2009). Mollusc shells grow incrementally as the animal ages, so a large shell is an old individual. Some species show incremental growth structures in shell cross-sections, which can be used to estimate age at death and season of collection. These incremental analyses, termed *sclerochronology*, have been successfully applied in many parts of the world.

The analysis of *stable isotopes* of constituent elements in bone and shell is making an increasingly important contribution to zooarchaeology (see ISOTOPES). Combined with *sclerochronology* of shells, analysis of oxygen isotope ratios ($^{18}\text{O}/^{16}\text{O}$) (see MOBILITY AND OXYGEN ISOTOPES) as a proxy record of water temperature can refine evidence of seasonal harvesting as well as providing environmental evidence. Oxygen isotope analysis has also been applied to mammal tooth enamel for paleoclimate records. Isotope ratios of carbon ($^{13}\text{C}/^{12}\text{C}$) (see DIET AND CARBON ISOTOPES) and nitrogen ($^{15}\text{N}/^{14}\text{N}$) (see DIET AND NITROGEN ISOTOPES) derived from bone collagen are used to investigate diet, the carbon ratio reflecting different sources of terrestrial and marine input and the nitrogen ratio reflecting trophic level. These dietary analyses can shed valuable light on the interaction of people and other species such as dogs and chickens by showing whether the animals had a similar diet to their human contemporaries, a useful criterion in recognizing companion animals (see COMPANION ANIMALS).

The strontium ratio ($^{87}\text{Sr}/^{86}\text{Sr}$) (see MOBILITY AND STRONTIUM ISOTOPES) is proving useful in zooarchaeology, usually measured in tooth enamel. This ratio is responsive to regional geology, being highest in ancient rocks such as granites and gneisses, and lowest in recent sediments and young extrusive igneous rocks. By comparing skeletal strontium isotope ratios with the ratio characteristic of the findspot, it may be possible to demonstrate that animals or parts of them were moved over considerable distances before deposition.

Turning from the practical to the more thematic, Paleolithic zooarchaeology necessarily focuses on hunting, and differentiating assemblages that result from people hunting from those resulting from scavenging, or even food debris of predators that have hunted people (Brain 1981). By examining bone surfaces to show, for example, whether predator tooth marks consistently underlie or overlie stone-tool cut marks, the pre-depositional processing of the bones can be determined. Disproportionate representation of particular body parts may also show whether acquisition was selective, with only certain parts of a carcass brought to a home base for consumption on the grounds that elements such as the head that were heavy but with a low proportion of usable flesh would be left at the kill-site. One weakness of this line of argument is that the edible internal organs such as heart and liver leave no archaeological trace, and the perception of what is usefully edible is subject to local custom and practice. For the Middle and Upper Paleolithic, the emphasis is more on prey selection and what this might reveal about the regional environment and decision making by the group. An important theme is the distinction between the highly targeted hunting seen, for example, in the Great Plains of North America and the broad-spectrum foraging seen, for example, in tropical Southeast Asia and southwest Europe. Optimal foraging models have been applied as explanatory devices, to show when narrow- or broad-spectrum hunting might have been the more efficient, but these approaches are not without their critics.

The exploitation of marine and freshwater fish in different societies has been a specialized area of study within zooarchaeology, not least because of

the particular challenges presented by the reliable identification of fish bones and scales (see FISH). The identification of intertidal, inshore, and offshore (see DEEP-SEA FISHERIES) fish species, especially when combined with studies of marine molluscs, can yield very detailed evidence of resource exploitation. Zooarchaeological data relating to species' past distributions and size range also make a significant contribution to contemporary debates on overfishing and the management of marine resources.

Unsurprisingly, animal domestication and its origins (see DOMESTICATION) have been major topics in zooarchaeology (Zeder, Emshwiller, and Smith 2006). A range of criteria has been recommended for the differentiation of wild and domestic forms of taxa such as caprines (see SHEEP AND GOATS) and camelids (see LLAMAS AND ALPACAS). These include changes in bone size and morphology, mortality profile, and distribution relative to a presumed wild range and habitat. Any of these would have to be accompanied by other archaeological evidence consistent with a pastoral or agrarian lifestyle, and none of them is reliably diagnostic. Size changes may indicate the emergence of a "domesticated" deme, but could also be an ecophenotypic response to some other environmental pressure. Changes in distribution might reflect the active translocation of domestic stock by people, but could be the consequence of community dynamics such as a reduction of predator pressure or regional changes in vegetation and soils. Much of the discussion of domestication in zooarchaeology has focused on caprine domestication in the wider Middle East, with a tendency to argue from that specific case to generalizing theories of animal domestication. As zooarchaeology has become a mature discipline in more parts of the world, the applicability of Middle Eastern or European models of animal domestication to other regions has increasingly been questioned, as has the underlying paradigm that domestication was a one-way process of people acting upon passive animal populations, and even the binary distinction between human and animal (see HUMANITY AND ANIMALITY). These trends in interpretation have revived interest in animal paleopathology (see PALEOPATHOLOGY). Signs of disease and injury in the bones of domestic livestock will reflect the management of those animals and

perhaps how they were regarded and valued. This approach has moved animal paleopathology away from simply “stamp collecting” interesting specimens of disease or injury.

In complex societies, especially in urban settlements (see URBAN ENVIRONMENTS), the population consuming animal resources is spatially and behaviorally removed from the production of those animals, adding a supply chain and further levels of decision making to the zooarchaeological interpretation. Contextual variation in assemblages from a large settlement may reflect socioeconomic stratification (“status”) or the location of carcass-based crafts such as tanners and horn-workers. Urban zooarchaeology presents distinctive challenges of spatial complexity and taphonomy, making a fine-grained contextual approach essential. However, the potential of an integrated analysis of bones, shells, and artifacts for detecting the socioeconomic characteristics of individual properties or neighborhoods is considerable.

Although zooarchaeology is largely concerned with the subsistence use of animals, animals living and dead have been used in ceremonial and symbolic ways since early prehistory. The inclusion of animal bodies and parts in human burials is widespread and often difficult to understand. For example, a Natufian burial from present-day Israel included remains of 50 tortoises and parts of a wild boar, a cow, a leopard, an eagle, and an additional human foot (Grosman, Munro, and Belfer-Cohen 2008). All or any of those animals could have been a social identifier, an offering for the afterlife, or the debris from a funeral feast. As archaeologists have become more aware of the symbolic social role of feasting in past societies, the recognition of feasting debris has become an important topic in zooarchaeology. Attention has returned to shell middens, now seen as having had a social or even ceremonial function. Care is needed here: One researcher’s food debris is another’s ritualized middening and yet another’s taphonomic palimpsest. None of those interpretations is necessarily wrong, and each of them may be the most useful interpretation given different research agendas.

Although the process has been a slow one, zooarchaeology has established itself as a significant discipline with a role to play in our

understanding of the human past. The recent development of “social zooarchaeology” reflects a desire to see animals as having played more than a subsistence role in past societies, even if the meaning of the term is currently rather fluid, and some argue for a recognition of animals as cultured entities with agency in the construction of human societies. Beyond archaeology, conservation science and neozoology have become aware of the importance of long-term baseline data on animal abundance and distribution (see BIOGEOGRAPHY), emphasizing the need for valid identifications and reliable dating evidence (Wolverton and Lyman 2012). The globalization of zooarchaeology is moving the center of activity away from researchers in western Europe and North America, diversifying the cultural basis of the discipline and raising quite new and stimulating research agendas. In Southeast Asia, in particular, zooarchaeology is having a real impact on wildlife conservation by demonstrating the past range of species now seen only in fragmented refugia. Furthermore, the prevailing European/North American tradition in zooarchaeology is being challenged and altered by paradigms deriving from societies that take a quite different attitude to animals and to the understanding of their excavated remains. The future of zooarchaeology lies in reaching out globally and intellectually to take in new insights and paradigms and to disseminate the information that the discipline generates.

SEE ALSO: Cattle; Conservation of Bone, Horn, and Ivory; Dairying; Domestication of Equids; Osteology; Zooarchaeology and Human Diet Reconstruction; Zooarchaeology and Human Trade and Migration; Zooarchaeology and Stable Isotopes

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Zooarchaeology and Ancient DNA

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In the seminal 1984 paper by Higuchi et al. (1984) that first showed the post-mortem survival of ancient DNA and initiated the entire field of ancient DNA studies, the authors used small scraps of muscle tissue found while remounting a specimen of the extinct quagga (*Equus quagga*). Using primitive bacterial cloning methods they showed that recognizably equine DNA sequences were still to be found within. From there, the field split into two main branches: those concerned with getting ancient DNA from human remains and those concerned with getting DNA from other sources. While the study of ancient DNA from human remains requires incredibly stringent laboratory protocols to prevent contamination, working on zooarchaeological material happily circumvents many of these issues due to lower risks associated with working on extinct species, rare specimens, and domesticates.

In the first decade of ancient DNA research, the analysis of zooarchaeological remains followed a clear pattern. When bacterial cloning methods were supplanted with the infinitely more powerful polymerase chain reaction (PCR), many groups identified species with poor taxonomic resolution and used phylogenetic methods to definitively place them within recognized lineages. During this phase, recently extinct species such as the Tasmanian tiger (*Thylacinus cynocephalus*) and woolly mammoth (*Mammuthus primigenius*) were analyzed from preserved remnants of tissue. Museums were suddenly reimagined as vast repositories of genetic information, and studies of extinct populations of living species or phylogenetic analyses of species so rare that field studies were impossible became a reality. Initial publications were conservative in nature, mostly confirming pre-existing hypotheses about relationships. The power of PCR allowed researchers

to experiment with alternative sources of DNA. In particular, the ability to extract high-quality DNA from subfossil bone, which is found in enormous quantities in permafrost regions, was a breakthrough that massively expanded the age of the material that DNA could be recovered from and opened up the Late Pleistocene as a period that could be studied through genetics. This expansion brought with it an avalanche of new questions related to population dynamics, ecological regime changes, and the nature of the megafaunal extinction.

However, at the same time, trouble was brewing. While some researchers were expanding the scope of questions that could be asked with ancient DNA within a short chronological time frame, others were simply trying to push back the age of putatively recovered DNA. Starting in the early 1990s and reaching a crisis point during the mid-decade, this singular agenda led to reports of DNA from Miocene fossils, Oligocene amber, and Cretaceous dinosaur bone. When these studies could not be reliably replicated, and further study suggested they violated the kinetics of DNA breakdown, the field lurched into a self-inflicted crisis of confidence. Trust was only recovered when a comprehensive set of guidelines were voluntarily adopted, with an emphasis on internal and external replication of results (see DNA: MITOCHONDRIAL and DNA: NEXT GENERATION SEQUENCING).

Since then, the use of ancient DNA in zooarchaeological studies has expanded considerably. Study of the phylogenetics of extinct species has become a useful tool to place unusual taxa within a standard taxonomy. Recovery of longer fragments from mitochondrial and nuclear DNA has shown definitively that traditional morphometric methods can be by turns too conservative or too radical. Good examples of this can be found in the study of New Zealand's recently extinct flightless moa (Aves: Dinornithiformes). Early work looking at variation in bones of this family vastly overestimated the number of species. Ancient DNA from well-preserved remains showed that species limits were quite clear genetically and

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the species contained appreciable morphological variation (Bunce et al. 2009). Similarly, the effects of sexual dimorphism had not been fully appreciated and it was only through recovery of sex-linked genetic loci that what had previously been classified as two morphologically distinct species could be correctly assigned as males and females of a single species (Bunce et al. 2003). In New Zealand the abundant remains of moa have also been used to explore traditional zooarchaeological questions about diet. Moa coprolites (see COPROLITES) have been used to reconstruct browsing and grazing niches in various extinct members of this family (Wood et al. 2012). DNA extracted from coprolites has the advantage of identifying both defecator and dietary remains that are too small or too degraded to be identified at the macroscopic level.

Questions of species abundance and demography have also been addressed in moa using a combination of radiocarbon dating and microsatellite data to show that populations were not in decline before human settlement of New Zealand (Allentoft et al. 2014). This approach was first pioneered in Pleistocene Beringian steppe bison (*Bison priscus*). The region known as Beringia (modern-day Siberia, Alaska, the Yukon, and the submerged landscape of the Bering Strait) has been the focus of huge research interest. As a crossroads between the Old and New Worlds, Pleistocene Beringia was a dry steppe grassland subcontinent with a fauna of woolly mammoths, woolly rhinos (*Coelodonta antiquitatis*), cave lions (*Panthera spelaea*), hyenas (*Crocota crocuta*), bison, horses (*Equus ferus*), and other species. The remaining areas within the permafrost zone provide a paleoenvironmental archive of vertebrate remains that allow the exploration of the transition from the Pleistocene to the Holocene. The permafrost conditions ensure that DNA is well preserved and remains of bison and other megafauna are abundant. Using combinations of radiocarbon dating and mitochondrial data, and employing coalescent theory (which states that genetic diversity varies in proportion to effective population size), it has been possible to graph effective population size (N_e) for a number of extinct and extant Beringian megafauna. Paradoxically, the data have shown that while some species (mammoth, rhino, horse) did not appear to go through a population bottleneck at

the end of the Pleistocene, bison went through a sharp decline at the beginning of the Holocene, yet recovered to become the most abundant large mammal in North America by the Late Holocene (Lorenzen et al. 2011).

Large-scale studies of population change necessarily rely on huge datasets consisting of hundreds of well-dated sequences with accurate provenance. The number of taxa for which this is possible are few, but even with smaller-scale datasets, vital information on population movement can be gleaned. Carnivores tend to be found at low density in ecosystems and are correspondingly rare in the fossil record. Nonetheless, they are often of major conservation concern and have been intensively studied using modern genetic analyses. A classic case is that of North American brown bears (*Ursus arctos*) and polar bears (*Ursus maritimus*). Until recently, brown bears were classified into static phylogenetic lineages, with an implied long history of separation and with polar bears nestling within the diversity presented by brown bears. Analyses of ancient bear remains have exploded this view of phylogeography, showing that various intraspecific lineages have been highly dynamic and wide ranging, sometimes retreating to refugia, other times expanding outwards and even hybridizing with related species (Barnes et al. 2002).

Despite the place that large-scale studies now hold within ancient DNA there is still scope for singular, well-preserved specimens to contribute. In these cases, deep sequencing (i.e., high-coverage nuclear genomes) of one or a few specimens can give as much information as shallower sequencing (i.e., mitochondrial DNA, or single locus) from scores of specimens. A good example of this has come to the fore with the development of next generation sequencing technologies that allow in-depth recovery of ancient genomes with high coverage. First pioneered in cave bears, the high-throughput systems allow access to nuclear genomes, including protein-coding genes that influence the phenotype and autosomal markers that give information on population history (Noonan et al. 2005). Since each gene in a diploid genome can contain two alleles it is possible to estimate how long ago those alleles diverged from each other. By comparing the alleles of many hundreds of genes from a single genome, it is possible to reconstruct in

a timeline where alleles converge, which corresponds to periods of low effective population size. This approach has been used in studies of Pleistocene horses, confirming that climate acted as a major driver of population change in the horse (Orlando et al. 2013). Alternatively, the effects of single genes can be analyzed. One of the first to be investigated, MC1R, is involved with coat color and has been sequenced from extinct mammoths, horses, and other taxa (Römpler et al. 2006). MC1R codes for a cell membrane receptor that when stimulated switches between production of red-yellow pheomelanin and brown-black eumelanin. Loss-of-function mutations are well known in modern species and lead to a pale/red phenotype in living animals. This ideal one gene>one protein>phenotypic effect cascade is perfect for studying ancient and extinct remains, allowing us to say something definite about the appearance of animals that is not preserved in the fossil record. Typing of MC1R in fossil mammoths has shown that there was coat-color variation: Some mammoths were dark-colored and some were perhaps blonde (Römpler et al. 2006).

The intersection of zooarchaeology (see ZOOARCHAEOLOGY) and ancient DNA has given us great insight into the process of domestication (see DOMESTICATION). Using ancient DNA it has been possible to test hypotheses about relationships between wild ancestors and domesticates. Going further, work has also used phylogeography to look at domestication at the population level: identifying regions where domestication may have taken place based on the genetic signatures of wild ancestors compared to modern domesticates and commensals. As human groups often took domesticates with them as they moved, signals of that movement can be found in the genetics of ancient remains. While humans are in general genetically uniform, their commensals and domesticates tend to contain a strong signal of regional origin, reflecting histories of expansion and contraction (Dobney and Larson 2006). These signals can be used to identify focal origins for human migrations, routes taken, and even timescales. A good use of this has been with domestic pigs (see PIGS), where multiple centers of domestication have been identified, including in the Near East, and it has been possible to track the introgression of Near-Eastern domestic pigs into Neolithic Europe and hybridization with

autochthonous wild boars (Larson et al. 2007). Ancient DNA therefore not only gives access to the progress of domestication but also provides insights into the process itself.

At the forefront of ancient DNA are new laboratory techniques that allow researchers to circumvent many of the problems traditionally associated with ancient remains. Poor preservation, modern contaminants, and co-extraction of inhibitors have all stymied ancient DNA analyses of important specimens and sites. New methods using bait RNA molecules to fish out surviving endogenous sequence show great promise in greatly expanding both the range of materials that can be accessed and the maximum age of remains from which DNA can be recovered. Researchers are also experimenting with alternative sources of genetic information including eggshell, soil, hair, parchment, and many other zooarchaeological remains.

SEE ALSO: Sequencing DNA; Zooarchaeology and Human Diet Reconstruction; Zooarchaeology and Human Trade and Migration; Zooarchaeology and Stable Isotopes

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Zooarchaeology and Stable Isotopes

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Stable isotope studies have become commonplace in archaeological investigations of human health, diet, and mobility, often underpinned by small comparative studies of associated faunal material. In recent years, the value of studying the isotope data of faunal materials in their own right has been recognized, allowing for detailed research into animal diets, changes in animal management, mobility, environment, and procurement, and what this may mean for human–animal relationships in the past (see ZOOARCHAEOLOGY).

The application of isotope geochemistry to studies of archaeological animal remains initially employed stable carbon isotopes, followed by combined stable carbon and nitrogen studies of bone collagen, to benchmark past human diets (see DIET AND CARBON ISOTOPES and DIET AND NITROGEN ISOTOPES). Small numbers of comparative samples tended to be drawn from a limited range of species with little or no appreciation that the study of the animals themselves could be of interest, either their populations or as individuals.

More recently, a suite of other biochemical isotopes extracted from archaeological animal remains (e.g., oxygen, sulfur, and radiogenic strontium) have been shown to offer enormous potential for disclosing critical aspects of human–animal interactions in the past: tracking the movement of animals at different scales, understanding animal diet and management, reconstructing their past environments, and revealing the complexity of culturally embedded social relationships. This entry uses carefully selected case studies drawn from recent

scholarship to explore each of these themes in turn and reflect upon the benefits and challenges.

Mobility

While not stable, radiogenic strontium isotopes are effective for characterizing human and animal mobility. $^{87}\text{Sr}/^{86}\text{Sr}$ concentrations vary according to local geologies; strontium isotope variability in bedrocks gives rise to soils that preserve the source geochemistry. Plants growing on these soils take up these local strontium signatures and pass them up through the food chain. Comparison of strontium ratios in tooth enamel with strontium ratios that have been mapped geographically thus affords the opportunity to track an animal's location as each tooth formed. Similarly, stable oxygen isotopes can be used to track the movement of animals through differential rainfall patterns and temperature gradients, which, in combination with strontium analysis, can refine where an animal was born and the locations in which it lived or was kept, before it became part of the archaeological record.

At Fishbourne Roman Palace in Sussex, the United Kingdom, for example, first-generation imports of fallow deer (*Dama dama*) were identified through isotope analysis. The strontium isotope ratio from a mandibular first molar dated to the first century CE indicated that it originated outside Britain. The strontium values from the second and third molars from this individual, which form later in life, exhibited a local signature. This strongly suggests that this deer was transported to England during the first year of life. Complementary analysis of oxygen isotope values from the same tooth reveals that the local signature equates to a warmer and drier location, likely the central or western Mediterranean, corroborating zooarchaeological evidence for the location of established breeding populations of fallow deer. Follow-up ancient DNA analysis (see ZOOARCHAEOLOGY AND ANCIENT DNA) mapped the specimen as genetically closer to Italian rather

than Turkish populations, suggesting a European introduction to Britain (Sykes 2014, 94).

Strontium analysis has also been used effectively to explore intra-national movement of animals. This was ably demonstrated at the mid-third millennium BCE causewayed enclosure at Durrington Walls, Wiltshire, UK (Viner et al. 2010). This evidence indicated the movement of cattle from multiple locations within Britain, carrying important implications for the mobility of people, the purpose of this type of site, and the nature of human–cattle relationships within Neolithic Britain.

In addition to the movement of living animals, stable isotope analysis has been used to reconstruct supply networks through the analysis of deadstock. An illustrative case study is provided by Barrett et al. (2011). Here, investigation focused on sourcing cod (*Gadus morhua*), which increased in frequency in northern and western Europe at the beginning of the tenth and eleventh centuries CE: part of what has been coined the “fish event horizon” (see DEEP-SEA FISHERIES). Based on the principle that stable carbon and nitrogen isotopes differ across marine regions due to variations in the length of the food chain, water temperature, and salinity, analysis of archaeological cod remains was used to distinguish local procurement from longer-distance transportation of preserved fish. The results suggested that consumer pressure from urban areas prompted the development of deep-sea fishing further afield on an almost industrial scale, because local fishing grounds were unable to meet demand.

Diet

While the isotopes of carbon and nitrogen can be used to reconstruct animal mobility (Barrett et al. 2011), they are more commonly employed in the analysis of animal diets. The ratio of the heavier to the lighter isotope ($^{13}\text{C}/^{12}\text{C}$ or $^{15}\text{N}/^{14}\text{N}$) varies across terrestrial food webs (Figure 1). Carbon isotope values are primarily influenced by the differential uptake of carbon by plants in photosynthesis, and can be used to distinguish diets based on C_3 or C_4 plants, marine, or terrestrial foods. Subtle variations in plant $\delta^{13}\text{C}$ occur in response to environmental factors such as light intensity,

aridity, rainfall patterns, temperature, elevation, and salinity. Nitrogen isotopes ($\delta^{15}\text{N}$ values) are influenced by the processes of nitrogen fixation and loss in soils, and their uptake by plants. The $\delta^{15}\text{N}$ value is then elevated by 3–5‰ at each trophic level: thus, plants have depreciated values relative sequentially to herbivores, omnivores, and carnivores; pre-weaned mammals, which effectively “consume” their mothers, are also positioned at a higher trophic level. Variability in the $\delta^{15}\text{N}$ of animals occurs in response to manuring of feed crops, growth rate of the animals, starvation, and environmental factors such as temperature and aridity. The uptake of isotopes of carbon and nitrogen from dietary sources, as differentiated by these factors, is preserved in protein-rich corporeal structures such as bone collagen, hair, skin, nails, horncores, and antler, which are in turn differentially preserved in the archaeological record (see FORMATION PROCESSES).

The analytical utility of dietary stable isotope analysis of faunal remains is apparent in a study of caprine and cattle material from the Early Neolithic (eighth–ninth millennium BCE) site of Aşıklı Höyük in Anatolia (Pearson et al. 2007). Here, a study of the bone collagen carbon and nitrogen isotope values countered the zooarchaeological interpretation that the domestic status of the animals was “unclear.” In essence, the isotope study showed that the sheep and goats had tightly clustered and overlapping values, indicating a common dietary source, close confinement, and management. Conversely, data for the cattle showed that these animals were free ranging, sourcing their diet from a variety of environments, indicating they were unmanaged and likely wild.

In contrast to the study at Aşıklı Höyük, stable isotopes can provide independent evidence to support interpretations drawn from zooarchaeological analysis. At Dudley Castle, West Midlands, UK, the animal bone evidence indicated a rapid change of pig management during the fourteenth century CE, testified by a decrease in numbers, increased body size, and a higher proportion of neonates (Hamilton and Thomas 2012). Stable isotope analysis of carbon and nitrogen was applied to establish whether there was a simultaneous change in pig diet. Analysis revealed no change in $\delta^{13}\text{C}$ values, but a significant decrease in ^{15}N across the population

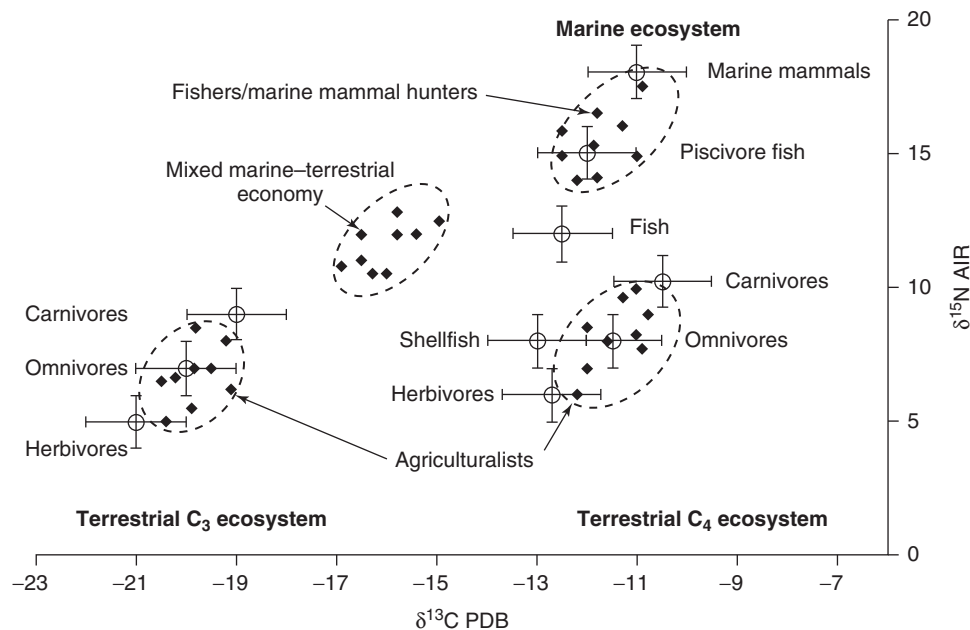


Figure 1 Scatterplot of typical carbon and nitrogen stable isotope values for humans and animals by dietary group. Isotope ratios (δ) are reported as parts per mil (‰) relative to international standards PDB AIR.

in the later fourteenth century, in contrast to the pattern observed for fallow deer and cattle, which did not change in this period. This altered pig diet is consistent with the consumption of legumes, or decreased consumption of microfauna and/or fungi, resulting from a new management strategy, likely sty farming (Hamilton and Thomas 2012).

Management

As the above case studies demonstrate, changes in dietary stable isotope values can reveal changing management practices in the past. Zooarchaeologists have long been interested in identifying the season of occupation/use of sites and resources to better understand human mobility and subsistence practices. Isotope biochemistry has been used to elucidate these patterns further, as well as to show how the animals themselves were kept. For example, sulfur isotopes have been used to show that, once established, the breeding populations of fallow deer at Fishbourne Roman Palace (see above) were moved. The site, close to the south coast of Britain, is part of an estuarine

environment that is affected by proximity to the sea. Sea-spray-affected graze can alter sulfur isotope values because marine water $\delta^{34}\text{S}$ is higher than that in terrestrial and freshwater environments. While some fallow deer had elevated $\delta^{34}\text{S}$ values, others did not, indicating that deer management practices and the location of the Palace's deer park changed through time (Sykes 2014).

In a study of resource management, oxygen isotope ratios ($\delta^{18}\text{O}$) have been recorded from incremental growth rings in cod otoliths recovered from Mesolithic sites from the mid-fifth millennium BCE in southern Norway in order to establish the time of fish capture, and therefore the season of use, of two sites: Skoklefall and Skipshelleren (Hufthammer et al. 2010). The $\delta^{18}\text{O}$ values of the final rings of growth, those at the edge of the otolith which is the material deposited at the time of fish capture, were consistent with cold water temperatures, thus establishing that the sites were in use during the late winter or early spring (Hufthammer et al. 2010).

As the example from Aşıklı Höyük shows, stable carbon ($\delta^{13}\text{C}$) and nitrogen ($\delta^{15}\text{N}$) isotope analysis has the potential to elucidate dietary

regimes, which, in turn, have been used to disclose husbandry and foddering strategies. In Britain, this approach has been used to examine the fauna of two major midden sites: at Llanmaes in South Wales and Potterne in Wiltshire (Madgwick, Mulville, and Stevens 2012). Exceptionally wide-ranging results for pigs, particularly in terms of $\delta^{15}\text{N}$ values, indicate diverse foddering strategies: During the British Neolithic (third to fourth millennium BCE), pigs fed in woodlands, but by the late Iron Age (last two centuries BCE) this was supplemented by the incorporation of household waste. Similarly, caprines appear to have been raised on land subjected to different degrees of manuring, representing differing household or community management of crops and livestock. These local and even household management signatures in the animals belie the idea of specialist and/or large-scale food producers in the late Iron Age (Madgwick et al. 2012).

Environment

Broader patterns of environmental change can be revealed through the analysis of stable isotopes from archaeologically recovered animal remains. Evidence from nine archaeological sites situated on salt-marsh land in Belgium, for example, have highlighted how the diets of domestic herbivores were transformed by the changing coastal landscape between the Roman and late medieval periods (first to fifteenth century CE) (Müldner, Britton, and Ervynck 2014). Bulk collagen carbon and nitrogen data showed how variations in the animals' diet at different sites over time were consistent with shifting animal management and environmental change. Coastal exploitation in the Roman period appears to have been limited and seasonal, whereas early medieval herbivores grazed coastal areas all year round, with carbon and nitrogen values showing an increased marine influence. In the late medieval period, sheep and cattle carbon and nitrogen isotope values from coastal and inland sites become more consistent, indicating disappearance of coastal marshes (Müldner et al. 2014).

Human–animal relationships

Most of the isotope studies of zooarchaeological materials described above focus attention on animals as units of economic production, typically at the scale of a time-averaged “herd.” This is as much a reflection of prevailing intellectual concerns, conditioned by contemporary perceptions of animals, as it is by the reality of the lived human–animal experience in the past. However, there are a growing number of zooarchaeologically informed stable isotope studies that recognize the cultural role that animals played in human society, identifying the need to consider both agency and individuality.

To take one example, a number of human burials from the Avar period cemetery of Wien-Csokorgasse, Austria, contain socially stratified grave goods, frequently including chickens. Zooarchaeological investigation reveals that the offerings were not random; women were buried with hens, while cockerels were interred with men, with the longer spurs occurring in the graves of relatively higher-status men—indicative of a society where cockfighting was an important signal of masculine identity (Kroll 2013). To investigate the proximity of the human–chicken relationship, samples of the humans and chickens were compared through carbon and nitrogen isotope analysis. Preliminary results suggest direct correlations between the $\delta^{15}\text{N}$ values of the humans and the chickens interred with them. This parallel indicates that the protein content of the diets of humans and chickens buried together mirrored each other, and that the human–chicken relationship was close in life (Sykes 2014, 134): Individual chickens belonged to and were buried with individual members of society.

Dogs are often included in dietary isotope studies of humans as their omnivorous eating habits mean that they are perceived as good proxies for human populations. Few studies focus on the role of dogs as individuals; yet, one of the strengths of isotope applications is that they can identify and offer important information about individual animals. An illustrative example is provided by Mackinnon (2010) who describes a small, round-skulled dog (comparable in morphology to the Maltese toy breed) buried alongside a 10- to 15-year-old child from Roman

Carthage, Tunisia. The dog exhibited a range of skeletal pathology, including congenital hip dysplasia, pronounced degenerative joint disease, and extensive tooth loss. Despite a permanently dislocated hip and crippling arthritis, which would have doubtless affected the animal's mobility, the dog had survived to an advanced age, suggesting that it had been cared for throughout its life. Dietary stable isotope analysis certainly supported this view: The dog had one of the highest $\delta^{15}\text{N}$ values recorded from Roman sites in the Mediterranean, indicating a diet unusually rich in protein.

Using $\delta^{15}\text{N}$ values as a broad-brush indicator, Sykes (2014) demonstrated shifts between human and dog diets through time in Britain, effectively indicating the proximity of the human-dog relationship in different cultural periods. In the Neolithic, Iron Age, and Roman periods, dogs and humans appear to have largely consistent diets, containing similar amounts of protein, thereby suggesting a commensal relationship. In contrast, during the Mesolithic, when dogs are thought to have been domesticated, and the Anglo-Saxon period, there is greater dietary spacing between dogs and humans, indicating that human-dog relationships were less entwined.

Traditionally, zooarchaeological research has focused on themes of diet, economy, and "ritual;" however, zooarchaeological theory and practice are being increasingly influenced by engagement with ideas emerging from the field of animal studies. Research inspired by these ideas emphasizes the agency of animals and the importance of the social relationships between people and the animals with whom they interacted. The case studies presented above demonstrate the complementarity of stable isotope and zooarchaeological approaches for addressing key questions about the cultural and socioeconomic role of animals in the past at multiple scales: from time-averaged populations to individuals. Carbon and nitrogen stable isotope analysis of animals provides a unique source of evidence concerning animal diet, but can also complement zooarchaeological and other sources of evidence for changes in animal management, environment, and procurement. Strontium, oxygen, and sulfur isotopes can be used to enhance understandings of animal management and environment,

and can uniquely disclose patterns of mobility in a manner that traditional zooarchaeological evidence cannot.

Interpretation is not always straightforward, however. Many factors affect the uptake of various isotope concentrations by plants, animals, and humans alike, and it is important that as much of this information as possible is understood prior to interpretation. Certainly, the selected case studies highlight the importance of grounding zooarchaeological and isotope studies in broader environmental and cultural contexts in order to interpret human and animal behavior. The use of isotope studies thus promotes a general need to better understand the holistic archaeological record, taking into consideration ecological, physiological, and osteological factors that affect both the taphonomy of samples and the reliability of isotope data, thereby increasing our knowledge of the human past as a whole.

SEE ALSO: Archaeological Sciences;
Archaeology; Bioarchaeology; Biogeography;
Chemistry in Archaeology; Diet and Sulfur
Isotopes; Diet and Trace Elements;
Environmental Archaeology; Isotopes;
Non-Stable Isotopes in Archaeology;
Zooarchaeology and Human Diet
Reconstruction

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Aerial Photography

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The interpretation of photographs taken from an airborne platform, also known as aerial archaeology, represents one of the most important advances in archaeology in the twentieth century. Combining the innovative advances of aviation and photography, one of the first aerial photographs (APs) of an archaeological site was taken when Lieutenant P. H. Sharpe photographed Stonehenge, England, from a war balloon in 1906. The First World War gave aerial photography a great impetus as both sides urgently needed intelligence on each other's activities, as well as improvements to their mapping of the battlefield. In addition to features of military interest, many new archaeological sites were discovered, and the value to archaeology became recognized. In 1917, German military aviators undertook photography of archaeological sites in Sinai, and in the same year Lieutenant Colonel G. A. Beazeley photographed the ruins of the city of Samarra in Iraq, as well as the network of ancient irrigation canals, watercourses, and settlements.

By the 1920s, the use of APs for archaeology began in earnest with the work of O. G. S. Crawford in England and Père A. Poidebard in Syria who both recognized the great value of aerial reconnaissance. Poidebard's work in Syria was mainly concerned with the Roman Empire's eastern desert frontier and a similar pioneering investigation was later made in Jordan and Iraq by Sir Aurel Stein just before the start of the Second World War.

Crawford's work mapping archaeological sites in England seen on Royal Air Force photographs was ahead of its time and his classic campaign of photography with Alexander Keiller, heir to the famous firm of Dundee-based marmalade manufacturers, aroused general interest with the publication of their book *Wessex from the*

Air (Crawford and Keiller 1928). Encouraged by Crawford's work, Major G. W. G. Allen began work in the Oxford region of England where he discovered a huge number of previously unknown archaeological sites that were revealed by marks in crops growing in farmland.

The Second World War brought a further increase in military aerial reconnaissance and presented archaeologists like J. S. P. Bradford with opportunities to take forward their academic interests while working on the interpretation of APs. Bradford made important discoveries in Italy and Yugoslavia, in particular the extensive crop marks found in parts of Apulia, which he subsequently published in his book *Ancient Landscapes* (Bradford 1987). Following the end of the war, the appointment of Professor J. K. St Joseph as Curator in Aerial Photography at Cambridge University established the first professional post in the subject and recognized the full potential of aerial photography for archaeology.

Today, APs for archaeological use are mainly taken from a light aircraft using hand-held cameras. The resulting photographs are oblique views of the landscape, although vertical APs taken by specialist aircraft and cameras, as well as unmanned drones, are also used. The advent of affordable high-quality digital cameras has meant that traditional black-and-white (panchromatic) and color films are now being replaced by digital photographs that have the benefit of being able to be transferred to the digital environment without the need for scanning of prints or negatives. False-color infrared films have also been used in the past but with mixed results as their sensitivity to over- or under-exposure made them difficult to use in the air.

Whilst oblique APs are relatively cheap to acquire, they are selective in nature, and are usually taken of sites observed by an archaeologist in the aircraft, or as seen on previous AP sorties, and hence cover only a small fraction of the landscape below. Vertical APs are more expensive and usually result from nonarchaeological surveys, but can provide comprehensive coverage

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of relatively large areas of a landscape. Both approaches have their advantages and disadvantages: Vertical photographs tend to be taken from a single pass over the landscape at a set altitude and provide overlapping cover giving stereo pairs, whereas oblique photographs can be taken from a variety of angles and altitudes around a site to take advantage of lighting conditions as the aircraft circles overhead. Oblique photographs are generally easier to view and interpret, and are good for pictorial effect and perspective, but require the use of specialist software in order to be transformed to a plan view. Once rectified and georeferenced to a coordinate system, both oblique and vertical photographs can be transcribed and integrated with other archaeological and landscape information in a geographical information system (GIS) to produce a comprehensive digital map of the archaeology of an area.

The types of archaeological sites that are apparent on APs are generally of two forms: Sites on which there are standing remains, and sites that have been levelled by agriculture (Riley 1987). They are usually described in the way in which the features are revealed, such as *earthworks*, *crop marks* or *soil marks*, rather than by the physical form that they represent. Thus *earthworks* represent features that can be seen in relief, such as banks and upstanding archaeological features, and are usually present in the form of highlights and shadows depending on the lighting at the time the photograph was taken. Where the color of the surface is relatively uniform, the shadows cast by low sunlight can provide most information. In arid regions where there is little vegetation, differences in the color of the stones of an archaeological feature and their surroundings may be apparent on aerial photographs. Low earthworks may also be revealed by drifting snow, as well as by differential flooding of the land.

Crop marks result from changes in the growth and color of crops on cultivated land when buried features either increase, or decrease, the availability of moisture and nutrients. Being sensitive to a range of factors including the type of crop and the date of sowing, the type of soil, and the weather during the growing season, crop marks can be transient in nature, standing out strongly one year, yet barely or not at all visible, the next.

Deep-rooted plants such as cereals like barley and wheat, and some root vegetables, are affected considerably by differences in the depth of soil and therefore are particularly conducive to the development of crop marks.

Areas of better crop growth generally result from deeper soil over filled ditches and pits where the conditions for growth are enhanced. Typically they are greener in color, taller and of a denser growth. Areas of poorer growth generally result from shallower soil over buried walls or other inorganic features where the plants tend to be stunted, paler green, and less dense in growth. Whilst grass is less responsive than cereal crops to differences in the underlying soil, differences in growth may occur in very dry weather with underlying features becoming apparent as *parch marks* on APs.

Soil marks are mostly visible on photographs of bare soil on cultivated land in winter months and show the presence of buried ditches, banks, or foundations through soil color variations. Generally, buried ditches appear as dark lines where material from their infill has been brought to the surface by ploughing, whereas the remains of levelled banks and mounds usually make lighter-toned marks. Differential moisture retention may also give rise to *damp marks* which fade when the soil dries and whilst many may have little archaeological meaning, others may provide an indication of buried features. Photographs of soil marks require careful interpretation as many natural features can influence soil color.

The considerable power of aerial photography for landscape survey can be seen from Palmer's (1984) seminal study of the landscape surrounding the Iron Age hillfort at Danebury in southern England. By using several thousand vertical and oblique APs he was able to map the archaeological features that had mostly been flattened by ploughing in a 175 square mile (450 square km) area around the hillfort and showed that it was surrounded by a complex agricultural landscape. At least eight other hillforts, over 100 farming enclosures and settlements, 7,000 acres (3,000 hectares) of ancient fields, 600 round barrows and ring ditches, of which 187 were newly discovered, and some 150 miles (240 km) of linear ditches were apparent on the APs. Through morphological analysis and the findings of the excavation of some of the settlement sites, he

was able to develop a series of period maps that documented the evolution of the landscape from the Neolithic to the end of the Romano-British period.

The Cold War continued the evolution of aerial photography through the development of photoreconnaissance satellites capable of providing high-resolution photographs from low earth orbit. In the 1990s, photographs from the Russian space program became commercially available and a study of a KVR-1000 photograph covering the environs of Stonehenge showed that it was broadly comparable with conventional medium-scale vertical aerial photography and capable of showing a range of upstanding and plough-leveled archaeological features (Fowler 1996). The declassification in 1995 of over 800,000 photographs from the US CORONA program provided public access to an extensive archive of previously highly classified high-resolution satellite photographs at very modest cost. Acquired between 1960 and 1972, and with near global coverage, the archaeological potential of the photographs was promptly demonstrated by Kennedy's (1998) study of the Greek and Roman cities of Samosata and Zeugma in modern Turkey. Since then, CORONA photographs have been used extensively, particularly in areas where conventional aerial photography is either prohibited or impractical, with Ur's (2010) mapping of over 3,700 miles (6,000 km) of premodern trackways in the vicinity of one of the largest Bronze Age sites at Tell Hamoukar in northern Mesopotamia demonstrating the huge potential of this resource. In 2002, further US intelligence satellite photographs were declassified including photographs from the GAMBIT program. Whilst GAMBIT had a higher resolution than CORONA, it was targeted on specific military and other installations in the former Soviet Union and China thus limiting its wider archaeological utility, but making the photographs particularly suited to studies of Cold War material culture.

High resolution images acquired by commercial satellites using panchromatic and multispectral sensors are now readily available and have been shown to have clear archaeological utility. The free availability of these type of photographs through virtual worlds such as Google Earth has generated a wider public interest in aerial archaeology and presents the potential for

the use of crowdsourcing to locate and identify features on archival images. When combined with archival photographs, recent satellite images can be used to monitor the condition of archaeological sites over time, particularly in areas of conflict identifying where areas of looting and damage can be identified.

The worldwide archives of millions of historical aerial and satellite photographs represent a considerable and largely untapped resource for archaeological survey and landscape analysis. With increasing online access to archives of digitized aerial and satellite photographs, and the development of GIS to aid their interpretation and analysis, new and unique opportunities are presented for the discovery of archaeological sites that have been destroyed through intensive land use and development, and for the development of new insights into the character of ancient landscapes.

SEE ALSO: Airborne Remote Sensing; Digital Cartography; Field Survey; Satellite Hyperspectral and Multispectral Imaging; Synthetic Aperture Radar

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Archaeological Videography

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Archaeological videography visually communicates some aspect of archaeological research and is either authored by archaeologists or through close consultation with archaeologists. Archaeologists have been using movies to document, explain, and publicize their research since the earliest days of cinema. These early films depicting archaeological research were often made by news agencies, particularly in the United States, United Kingdom, and other countries in western Europe and typically showed archaeological expeditions in far away “exotic” locations such as Egypt or Palestine. Several online archives including Europeana, Movietone, the British Pathé News Archive, and the Associated Press Archive feature excavation footage dating from the 1920s. This footage is of excavations in both local and foreign locations; the nonlocal excavations would often contain establishing shots that showed fantastic landscapes, locals in traditional attire acting as field staff on the excavations, and site directors framed as authoritative explorers in military-esque garb. Local archaeological excavations were also featured in much the same way, with an authoritative male archaeologist addressing the camera or giving visitors a tour while laborers excavated behind him. These tropes have reappeared throughout the history of archaeological videography, and reinforce the understanding of archaeological investigation as searching for treasure with triumphalist, nationalistic undertones.

In addition to appearing in front of the camera, archaeologists have long collaborated with documentarians to create film productions about archaeology and the past. Notably, in 1944 the Ministry of Education in the United Kingdom commissioned Jacquetta Hawkes to create a film on British prehistory. The making of this wartime

film is documented by Christine Finn (2001) who notes the prevalence of the narrative of invasion in the context of prehistoric Britain. Similarly, in the early 1950s in the United States, the Archaeological Institute of America produced a series of documentaries about the past. Ray Garner, the filmmaker in charge, was particularly concerned with verisimilitude in past violent action and used naturalistic visual metaphors such as thunderclouds sweeping over the mountains to depict ancient battles.

While archaeologically themed broadcasting began on television in the 1930s (Perry 2017), the programs *What in the World?* in the United States and *Animal Vegetable Mineral?* in the United Kingdom, which had scholar-contestants try to identify various artifacts, further popularized the format in the 1950s. Building on the success of these programs, archaeological documentaries became a mainstay of British and American television. By the 1970s there were enough archaeological documentaries to warrant a round of publications regarding useful titles for teaching archaeology, followed by a book of film reviews, *Archaeology on Film*, published by the Archaeological Institute of America in 1983. At the same time, changes in visual media technology such as the move from 16 mm film to videocassette and the proliferation of videocassette recorders (VCRs) made video production and distribution less expensive, increasing the availability of archaeological films and broadening nonspecialist access to production. Though systematic video recording was mentioned in the early 1990s as useful in archaeological excavation for a more complete visual record and its use considerably elaborated on sites such as Çatalhöyük (Tringham, Ashley, and Quinlan 2012), the time required to sort and edit film made extensive recording impractical. Much of this informal excavation footage is now unavailable as a result of format obsolescence and lack of formal archival strategies. Even as participation in both formal and informal video production increased, there was very little critical examination of archaeological film until Angela Piccini's (1996)

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discussion of the construction of Celtic people in documentaries wherein she questions the audience for archaeological films and the construction of a pan-European Celtic warrior aristocracy.

The technological shift to the use of digital media for filmmaking in archaeology has had a profound effect on authorship, content, quantity, production, and distribution of archaeological knowledge (Morgan 2014). Smartphones have become more popular, capturing relatively high quality archaeological images, and video has moved from a specialist role on archaeological projects to a ubiquitous exercise regardless of the position of the participant on site. Paired with the wide distribution available on social media, videos made by students can rapidly eclipse formal publications in terms of the dissemination of information about an archaeological project. Accordingly, the quantity of available online archaeological footage has rapidly increased as distribution of current media is uploaded alongside the growing collection of archival footage. As a result, archaeological movies made by professional documentarians in collaboration with archaeologists can be viewed alongside those made by students with smartphones or even those made to advance pseudoarchaeological claims, with little to distinguish the authority of the author.

There have been some efforts to collect and distribute authoritative archaeological films on dedicated web pages such as Past Horizons and The Archaeology Channel; the latter also hosts an annual film festival in the United States. There are several other annual and semiannual archaeology film festivals, such as AGON: International Meeting of Archaeological Film of the Mediterranean Area, Arkhaios Cultural Heritage and Archaeology Film Festival, CINARCHEA: Festival du Film d'Archéologie d'Amiens, FICAB: International Archaeological Film Festival of the Bidasoa, International Festival of Archaeology Films, Nyon; Festival International du Filme d'Archeologie de Besançon, ICRONOS: Festival International du Film Archeologique de Bordeaux, International Archaeology Film Festival in Split, KINEON: International Archaeological Film Festival of Brussels, and Rassegna Internazionale del Cinema Archeologico di Rovereto. In addition to these film festivals, there

are often short films shown at archaeological conferences.

Though the technology available for making videos has changed over time, genres of filmmaking within archaeology have remained relatively static. Most archaeological videos used to teach archaeology or for public outreach are *expository*; these hearken back to the old newsreels as they are didactic, with authoritative “voice-of-god” narration, expert “talking head” interviews interspersed with action from “on location” shots that follow narratives of discovery with soundtracks laden with “traditional,” flute or drum-heavy music. While these are the most common and clichéd form of archaeological videography, they remain useful for straightforward storytelling and are accessible to broader audiences. The *direct testimonial*—sometimes referred to as a “video diary”—is an account of current finds and conditions on site. Archaeological video diaries are likely to have derived from the practice of site tours, during which the archaeologist would relay information about the stratigraphy and any interesting finds to a small audience. There are a handful of *impressionistic* archaeological videos, which explore the space between art and archaeology. These videos celebrate subjectivity and lack the authoritative voice-overs and didactic structure of expository film, but can be frustrating to audiences who expect tidy narratives about the past. Finally, *phenomenological* films grant the viewer the gaze of an archaeologist by filming at eye level and recording the sensory components of archaeological fieldwork in a single, continuous shot. This genre has increased in popularity in conjunction with smart phone cameras and social media, wherein short videos can be featured alongside static photographs. None of these genres is exclusive; some videos feature aspects of two or more of these genres.

While archaeological documentaries are still relatively conservative in content and scope, archaeological videography is an exciting and increasingly porous medium with new formats such as animated GIFs, remixes, machinima made in virtual worlds, head-mounted action cameras, video podcasts, “let’s play” video gaming commentaries, animations, and drone footage

shifting and changing how we present our interpretations of the past. These videos can be embedded within other social media platforms and viewing interfaces can stream videos in a sequence, or presented as a nonlinear series of choices to jump between topics. Though the future of archaeological videography presents a broad array of creative ways to present archaeological research, it is a threatened format and amounts to so much digital ephemera without an increased attention to archival strategies that incorporate multimedia. Helpful guidance for the preservation of digital video can be found at the Archaeology Data Service (http://guides.archaeologydataservice.ac.uk/g2gp/Video_1).

SEE ALSO: Archaeological Photography; Creativity; Digital Media in Archaeology; Imaging; Photorealism and Digital Reconstruction; Public Archaeology

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FURTHER READINGS

Augering

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Augering in archaeology has often been conflated with coring (see CORING), but each has distinct methodological advantages and disadvantages. Augering refers to the removal of a sediment or rock sample in discontinuous segments, which disturbs the overall context and (without proper methodological considerations) may hinder inferences regarding landscape structure. Coring removes sediment or rock samples in a continuous cylindrical section (Stein 1986). However, in comparison with traditional excavation methods, augering is far less destructive, and more cost and time effective. The appropriateness and feasibility of using augering or coring to test a site for future excavation or to determine the concentration of artifacts has been heavily debated within the literature. Augering was first introduced into archaeological practice around the mid-1930s as a means of collecting sediment for the relative dating of archaeological deposits. Augering has since become increasingly important in contemporary archaeological investigations to examine buried sediments, ancient depositional environments, and the structural integrity of the landscape (Stein 1986). Augering offers distinct advantages over coring, which makes it a suitable method for geoarchaeological assessments of regional landscape ecology (see GEOARCHAEOLOGY).

Archaeological research has employed augering in various fashions since its first implementation in 1935. Stein (1986) defines the initial use of augering from 1935 to 1955 as “Period I.” Augering played an important role in the relative dating of archaeological deposits during this 20-year period. Specifically, research by Louisiana State University, Department of Geography and Anthropology implemented augering as a key method in their research projects in the Lower Mississippi River Delta throughout “Period I.” These early investigations extracted

river sediments in order to date corresponding archaeological remains (Stein 1986). There was a distinct shift in methodological applications and theoretical considerations of augering around 1964. Corresponding with both the introduction of radiometric dating and the processual critique of culture-historical archaeology, the feasibility and appropriateness of using augering to test ecologically driven research questions was debated. Beginning in the mid-1960s, augering became less important as a tool for dating an archaeological site and more important as a tool to reconstruct the landscape and collect sub-surface soils and sediments. In the late 1970s, augering was also employed in exploratory investigations, which sought to determine distinct site boundaries on the landscape (Stein 1991). The post-processual critique of archaeology and the increased value of human agency in human–environmental interaction increased the usefulness and feasibility of augering in anthropological archaeology methodologies. The usefulness of augering was at the forefront of another debate in archaeological literature in the early 1990s over “research” versus “cultural resources management” (CRM) projects. Stein (1986) defines the period from 1964 until the present as “Period II,” though Schuldenrein (1991) argues that a “Period III” began around 1970 and intensified with the implementation of augering in CRM projects (see CULTURAL RESOURCES MANAGEMENT). It is clear that these arbitrary period distinctions are associated with a larger schism in the field during this period between academia and public archaeology. However, despite potentially different research questions/agendas, augering was employed in both areas of archaeology as a less-invasive (compared with traditional excavation) and cost-effective means of examining the relationship between landscape features. Landscape ecology studies have defined the current emphasis and use of augering, especially in a growing number of interdisciplinary geoarchaeological investigations. These investigations often employ augering to collect sediment samples for physical

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and chemical analysis. Sediment samples not only inform the greater geomorphology of the area, but also help socioecological research questions examining the changing human–environmental dialectic throughout the archaeological record.

A majority of archaeological investigations that employ augering as a key method, especially interdisciplinary archaeological geology projects, examine socioecological dichotomies on a regional scale. Specifically, geomorphological assessments (see *GEOMORPHOLOGICAL SURVEY*) of current landscape conditions are adopting ecological theory as a means of correlating landscape structure with the spatial patterning of archaeological deposits (Stafford 1995). The utility of augering in examining the density of archaeological deposits though has also been debated. Howell (1993) compared the subsurface artifact densities extracted from auger probes versus 1 m by 1 m test excavations. Auger probes yielded fewer artifacts than the test excavations, though this is expected due to differences in scale. Augering has been widely viewed and cast as a “pre-excavation” method or a means of evaluating the best areas to excavate in the future. However, interdisciplinary applications of augering place greater importance on its utility as a primary excavation method. Augering can be a key component in extracting the subsurface sediments and soils that inform geomorphological patterns, though distinct disadvantages have been noted (Stein 1986; 1991; Stafford 1995). Stein (1986) highlights that the key advantage of augering and coring is their ability to define both the vertical and horizontal extent of archaeological sites. However, the boundary between cultural and noncultural material is often difficult to define. Augering may also be as labor intensive as other methods (Stafford 1995), while consistently mixing subsurface material (Stein 1991), conflating the interpretative value of the data. However, the advantages outweigh the possible methodological disadvantages. Since augers lack the cylindrical tube used by coring devices, they can penetrate a greater variety of subsurface material (Stein 1986; 1991). Augers are also capable of extracting larger volumes of material quicker than other coring methods, while providing a finer control over the extraction interval. Control over the extraction interval allows augers to overcome and reduce the

hindrances of mixed material, providing an accurate picture of subsurface structure (especially across a larger regional level) (Strafford 1995; Stein 1986).

The most implemented form of augers across archaeological investigations is the bucket hand auger. The bucket hand auger is a manual variant, which is turned using a T-bar. The T-bar is connected to the auger through a simple metal pole, which may be extended to reach greater depths. Some investigations employ powered augers, though there are significantly greater costs in comparison with manual hand augers. An auger extracts samples in a helical motion by cutting into the deposit using two cutting bits, which can vary depending on the underlying subsurface geology of the soil (sand, silt, clay, etc.). As the auger is turned, the cutting bits force material into the bucket for extraction (Stein 1986). Control over the extraction interval can be as fine as 10 cm in length and anywhere from 5 cm to 12.7 cm in diameter (Stafford 1995). One of the key advantages of bucket augers is their size. They allow archaeologists to assess areas that may not be amenable to traditional excavation methods. Each individual auger probe yields less material in one probe than other traditional excavation methods, but is highly representative of its context (Garrison 2016). Only a small amount of material from each probe is necessary to conduct a variety of physical and chemical tests, providing researchers with an easier way to characterize the spatiality of socioecological dichotomies across the landscape. Overall, bucket augers also allow one to extract a large volume of material quickly and cheaply at a variety of depths by using 1-m extension bars, providing a more accurate picture of stratigraphy, geomorphology, and site boundaries than coring methods (Stafford 1995; Stein 1991; Canti and Meddens 1998). The potential maximum depth of the deposit must be considered. Additional extension bars make it increasingly difficult to extract the bucket without any contamination from upper strata. In comparison to mechanical coring, augers also do not compact the layers as some percussion drilling methods or obscure changes in soil color and texture (Canti and Meddens 1998). When extracting sediment samples, it is best to collect directly from the bucket so as to avoid any potential contamination with other soils. Once

a subsurface soil or sediment has been sampled, a fairly accurate and complete picture of the horization of the auger probe can be achieved by dumping each bucket out on to the surface in a straight line. It is important to gain a minimum quantifiable number of probes in each landform visible in the regional landscape investigation. Three or more auger probes (at a minimum) in each distinct landform are usually sufficient in a regional-scale investigation in order to determine socioecological spatial distribution. Auger probes have also been used to accurately characterize the geomorphological differences along a catena by sampling along a transect.

Augering has been applied in a variety of contemporary socioecological research projects (see ENVIRONMENT AND LANDSCAPE). For example, Whalen (1990) used auger probes to delineate and define the distribution of buried features on the landscape. Whalen (1990) demonstrated that augering is an effective means of subsurface testing across large research areas in El Paso, Texas, while also providing expectations to guide later planned excavations. Cultural resource management projects, highlighted by Schuldenrein (1991), have also successfully applied augering in various projects. Rutherford (2014) conducted a survey in northwest England using auger probes to locate peat deposits before an impending development project continued. However, interdisciplinary applications of augering have shifted from determining the spatial distribution of individual archaeological sites, to accurately determining the distribution of activity patterns on the landscapes. Subsurface soils and sediments collected in each auger probe are subsequently analyzed using a variety of physical and chemical techniques (i.e., munsell, soil texture, trace-element quantification, soil organic matter analysis) to determine the degree and extent of anthropogenic pressure placed on landscapes. The degree of human-induced environmental pressure allows socioecological research projects to evaluate the legacies of past and contemporary actions on the future of the landscape. Contemporary uses of augering in archaeology have transcended both processual and post-processual research agendas and have been incorporated as a method in projects utilizing a variety of interdisciplinary theoretical approaches. Some have argued that this line of

research is uniquely suited for archaeologists because of their understanding of a deep time scale. Past interdisciplinary socioecological research projects that have employed augering as a key method have often been concerned with evaluating how the environment impacted past societies (Stein 1986). However, recent research has reversed this theoretical approach. Research being conducted in the Caribbean has utilized auger probes to conduct a geomorphological assessment of landscape conditions to evaluate how historic landscape use is impacting contemporary environmental conditions. This provides interdisciplinary research teams with a means of evaluating the impact of environmental pressures on contemporary populations, recognizing that these pressures may be legacies of prior anthropogenic landscape exploitation. Contemporary uses of augering are helping to mitigate the pressures faced by contemporary populations utilizing a variety of anthropological, theoretical, and methodological principles. Augering since 1935 has been used in a variety of contexts, but across all research projects has provided a quick, cheap, and less-destructive alternative to traditional archaeological excavation.

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Coring

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Coring is the removal of a minimally disturbed vertical profile of small diameter from any sort of substrate that can be penetrated with the chosen implement. In some geological applications, this penetration can go through solid rock and deep into the earth's crust, in a search for fossil fuels, minerals, and metals. Dendrochronologists take small wooden cores, generally referred to as increment borings, for tree ring studies. Very long ice cores with essentially continuous coverage of up to several hundred thousand years have been drilled in the ice packs of Greenland, Antarctica, and even high tropical mountains. In archaeology, the coring of marsh and lake sediments has been a key to analyses of fossil pollen, spores, charcoal particles, diatoms, and many other types of evidence for past environments and human traces on the landscape.

Sediment coring undertaken by archaeologists and their paleoecological collaborators in wet, or even underwater, substrates has been used successfully, in coordination with excavation efforts, to inform regional contexts about important archaeological complexes (e.g., McNeil, Burney, and Burney 2010). At richly fossiliferous sites such as caves, coring has served as a tool for choosing, in a large archaeological site, the richest areas for excavation through techniques for relatively undisturbed recovery down to five meters or more below the water table (Burney 2002).

Coring as understood by soil scientists has also been extremely useful to archaeologists in the sampling and description of soil layers over and around a site, whether wet or dry. In landscape archaeology, scientists have mapped the full extent of large anthropogenic deposits, human middens, and extreme event sites (such as megafaunal kill sites) by coring a grid pattern over a deposit and then by recording layer descriptions that can be used to extrapolate the full extent of

the deposit in terms of depth and thickness of the recognizable layers (often marked by cultural deposits) and to obtain a three-dimensional representation. Through radiocarbon dating, cultural seriation, key macrofaunal and botanical identifications, and other stratigraphic methods, detailed archaeological studies can be made with minimal effect on the site. Care should be taken, of course, to minimize research impacts by taking only as many small-diameter core samples as is prudent and by avoiding areas likely to have a high concentration of human materials. This methodology, rather than test-pitting or more extensive excavations, can aid in the conservation of cultural resources by establishing their full extent—as well as the state of preservation of the landscape surrounding the place of interest—with the help of relatively noninvasive techniques.

An important caveat related to the direct archaeological application of coring techniques is that, by definition, they are a blind probe. Ground-penetrating radar and underwater sonar can be a useful prelude to the selection of coring sites in situations where coring is available and can work. Care should always be taken to core only very judiciously, in the vicinity of a known rich site. Still, in cases where human evidence is scattered over a landscape of interest but no suitable concentrated sites are yet known (suitable for paleoecological and archaeometric studies, for instance), initial coring can greatly aid in discovery.

Coring devices

There are many types of coring devices that have proved to be directly useful to archaeological research.

Open drive samplers are the simplest imaginable devices for taking a short core in wet or moist sediments that are not too fibrous or coarse-grained. The procedure related to these devices consists of driving a thin-walled hollow tube into a substrate soft enough to allow passage. With very soft wet sediments, the tube will go

down easily in many cases, but the challenge is to pull it up without having the mud sucked out of the bottom by the opposing air pressure or, in the case of coarse sediments such as sand, simply pulled out by gravity. A second problem is that, if the downward cutting tube hits a very compact layer (and sediments become more compact with depth particularly when they are constantly under water), the plugged pipe may drive on, but without sampling the lower layers or with only a compacted and/or partial recovery.

In some cases, capping the top of the pipe before removing it can produce enough of a pressure seal to help hold the column of material in the tube (as any child with a straw and a milkshake discovers early on). The development of improved techniques such as *piston coring* in the mid-twentieth century led to an explosion of paleoecological research in lake sediments, often with large contributions to the archaeological interpretations of background climate change and inferred human effects.

A simple device of this type for coring in the mud of lakes and marshes consists of the coring tube, mounted on a strong rod that can be used to push the tube down and extract it. Inside the tube, initially at the bottom, there is a simple piston with rubber gaskets that can make a tight pressure seal. From the back of the piston, a steel cable extends to the surface. When the coring drive starts, at the top of the sediments being sought, the steel cable is fastened securely to an anchor point on the surface. The rod system is then pushed downward into the sediment, but, if set correctly, the piston will stay at the top of the sediment column until the full drive is reached (at this point the piston is at the top of the tube and maintains hydrostatic pressure). The rod can then be drawn up and the sediment will be enclosed in the tube. The piston is removed from the top, both ends of the tube are tightly corked and capped, and the outside is labeled as to measured depth and top-bottom orientation (with care, compass direction can be recorded as well, for use with paleomagnetic research methods).

Normally these drives are taken in 1-meter increments and, with thicker sediments, another tube (and another and another) can be loaded onto the rods. At the beginning of each drive,

the piston is reattached at the bottom of the new tube and the cable is advanced to reach the desired surface, now down in a hole that needs to be refound (if under water). In any case, the hole must be entered with minimum disturbance in order to satisfactorily collect the next meter. Cores over 50 meters long have been taken by this method. In many scientific circles, this type of piston corer, so widely used in paleoecology and paleolimnology, is called a Livingstone sampler, after Daniel Livingstone of Duke University. Although Livingstone was generous in pointing out that he was not the inventor of the device, he was probably the first to demonstrate very successfully its use in lakes and marshes of many types in North America and throughout Africa; thus he initiated a global network of coring sites from hundreds of researchers that provides a unique view into the planet's geologically recent past. The addition of drop-hammer devices designed to increase the driving power of the system, of chain hoists or other extraction devices designed to raise the generally resistant tube, and of a casing pipe for rod coring in deeper water made the Livingstone standard equipment in a wide range of paleoecological projects, including many focused on questions of direct relevance to archaeologists.

Ultimately a self-triggering, rodless system suspended on a cable made piston coring feasible even at great ocean depths. The Deep Sea Drilling Project (DSDP) and other large-scale international efforts have cored the oceans of the world even in very deep water, where sediment records that go back millions of years can sometimes be reached—and, with very fine resolution, even down to annual layers, though such cases are very rare. The Kullenberg sampler piston corer has thus played a direct role in scientists' understanding of Ice Age climate cycles and their effect on the biota and on human ancestors.

Peat deposits, the decayed and compacted remnants of ancient bog surfaces, have created special opportunities for and limitations to coring that are of interest to archaeologists. From the earliest pollen diagrams published in Europe a century ago to some of the most exciting finds in human-related paleoecological research in recent years, various types of peat borers have played an important role in archaeological and

human-related paleoecological studies. Early examples were gouge corers and augers that brought up a monolith of peat by shoving down a sharpened tube, later refined by side-sampling models such as the Hiller borer and the Russian peat borer. Just as with piston samplers, there are many commercial brands and trade names that are available. A correct generic term for the Russian peat borer is D-section corer. The device, in closed position, is shoved down to the desired depth in soft viscous sediment. The T-handle at the top of the rods is turned 180 degrees to open the sampler, which scoops the sediment from the side of the corer, ideally in a smooth semicircular cut, then holds it inside until the borer is extracted. The obvious disadvantage (in some circumstances) over piston coring is that the sample must then be subsampled into clean sealable bags or vials before the corer is returned to the hole, thoroughly cleaned and now in closed position for the next drive.

Quite good stratigraphic recovery is possible, as has been shown in many recent studies involving careful dating and multiproxy analysis at close intervals (e.g., De Boer et al. 2014). One advantage is that the stratigraphy can be seen immediately and described in fresh condition—and uncompacted by using a piston to extrude a piston-core sample from its pipe, or disturbed laterally by sawing open the pipe. D-section cores are probably the best possible system, in manageable sediments, for the minimally disturbed recovery of plant macrofossils and insect parts. Work in these areas has been important in archaeology for characterizing prehuman versus anthropogenic biota on islands colonized by humans and for establishing the timing and extent of major human-induced landscape changes, such as increased burning of vegetation near a site and its effects.

A wide variety of *soil augers* have been used in archaeological studies for describing the soil context around a cultural site. A favorite one for the quick and reasonably accurate assessment of soil types, middens, and artifact scatters is a “mud-head” type of soil auger with a 2–4-inch (5–10 cm) diameter, angled steel blades at the bottom, and a cylindrical basket that catches about one foot (30 cm) of anything loose enough to come up with circular digging—including

wet (or even dry) soils, fine gravel, shell fragments, unconsolidated volcanic ash, and lithic debitage. Through careful measurement and use of color and texture charts for standardization, soils and sediments can be characterized over several hectares per day in typical field situations. Samples can be photographed and described in the field and, if they are desired, the resulting holes are refilled with marker material (clean sand or fine gravel is good for contrast). Resulting sediments can be bagged for archiving and lab analyses such as flotation for seeds and screening for plant and animal macrofossils.

Site integration

These landscape-level archaeological techniques have greatly assisted in the assessment of important sites, conservation planning, and the discovery of rich artifactual, ethnobotanical, and zooarchaeological deposits. Great strides have been made in recent years through the discovery and study of archaeological sites that can be considered truly *integrated sites*, where current methods in archaeology include the use of coring and other techniques for the recovery of background information on the paleoenvironment of the site. In practice, the ideal site preserves a wide range of materials in good condition and has only minimally mixed sediments.

SEE ALSO: Lake Deposits; Paleoenvironmental Reconstruction; Palynology; Peat Deposits; Soil Survey

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Cosmic-Ray Muon Tomography

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Introduction

Cosmic-ray muon tomography is a passive, nondestructive method for imaging internal structures of large objects, pyramids for example, that are opaque to illumination by light, X-rays, or radar. Muon tomography employs muons: charged subatomic particles found in cosmic rays that have physical properties quite different from light. Cosmic-ray muons continually rain down on us from the Earth's upper atmosphere, penetrating ordinary matter to well under the Earth's surface, and they can be detected and tracked to create images of the location and density of material along their paths.

Luis Alvarez (Alvarez et al. 1970) invented muon tomography in the 1960s to address an archaeological conundrum: of the large pyramids at Giza, why did the Second Pyramid built under Chephren and only slightly smaller than the Great Pyramid of Cheops, not appear to have the elaborate chambers and passageways found in the Great Pyramid? Did Chephren cleverly hide similar structures in the Second Pyramid, or did they not exist? By 1965, when Alvarez proposed to explore Chephren's pyramid with cosmic rays, the role of muons in nature was still somewhat a mystery, but their interaction with ordinary matter was well understood, and technology for detecting muons existed to determine their paths through 100 meters or so of the pyramid's limestone with precision sufficient to resolve the conundrum. Alvarez was able to conclude: "We can say with confidence that no chambers with volumes similar to the four known chambers in Cheops's and Sneferu's pyramids exist in the mass of limestone investigated by cosmic-ray absorption." It would take another quarter-century

before muon tomography was applied to geophysical research (Nagamine 1995)—to image volcanoes—and not until the early 2000s was it considered again for archaeological (Melesio 2014) and national security (Borodzin et al. 2003) applications.

The muon and other particles

The Standard Model of particle physics (Particle Data Group 2015), formulated in the decade following Alvarez's pyramid study, classifies particles of matter according to their interactions with other particles: "hadrons" interact via all recognized basic forces—the strong nuclear force, electromagnetism, and weak forces responsible for nuclear beta decay—and "leptons", which do not interact through the strong nuclear force, but do via the others. Atomic nuclei are hadrons; electrons and muons are leptons. (The Standard Model also includes "force" or "field" particles, of which the photon is the most familiar; it is the particle that enables sight and imaging.)

Atomic nuclei interact so strongly in tenuous air molecules in the upper atmosphere or limestone in a pyramid that they simply do not penetrate very far through ordinary matter. Leptons are capable of penetrating longer distances. Neutrinos are uncharged and only rarely interact with anything; they can be detected, but are hopeless for imaging. Muons are electrically charged, like electrons, and interact relatively weakly with atoms. Their interactions in matter at the high speeds of cosmic rays produce two effects important to muon tomography: (1) they scatter—deflect repeatedly and randomly over relatively small angles by electric forces; and (2) they ionize some of the atoms they encounter, slowing down slightly with each encounter. Scattering will determine the ultimate precision to which a muon trajectory can be measured, and ionization (the same mechanism that creates health hazards associated with "radioactive" materials) will eventually stop a muon, at which point it will be captured by an atom or decay,

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either of which attenuates the number of muons passing through matter.

Muons are unstable, decaying to electrons and neutrinos with a mean lifetime of $2.2\ \mu\text{s}$ after their creation. The muons we use travel close to the speed of light, which, through the magic of Einstein's time dilation effect, permits them to travel many kilometers before decaying, whether in air, limestone, water, or vacuum. Cosmic-ray electrons, owing to their smaller masses (about 0.5% that of a muon's), suffer catastrophic collisions with ordinary matter, causing their energy to be dissipated within centimeters upon entering matter at ordinary density.

The point of all this detail is to highlight the fact that muons, of all the particles in the sub-atomic zoo, are *uniquely* suited for cosmic-ray tomography: they can penetrate many meters of ordinary matter, but are not so penetrating as to escape detection; they are electrically charged, enabling them to be tracked accurately by following their ionization path; and their numbers are attenuated by the total material each muon traverses, providing a basis for image contrast based on material density. Most important, Nature provides these useful high-energy particles around the clock, everywhere on Earth.

Origins of cosmic-ray muons

Muons are products of weak decays of hadrons created near the top of the terrestrial atmosphere by energetic collisions of "primary" cosmic rays with molecules of Earth's atmosphere. Primary cosmic rays are atomic nuclei accelerated to very high energies by some of the most energetic processes in the cosmos; they travel galactic distances at essentially the speed of light before encountering Earth. Our planet and all life on it is shielded from these hazardous particles by the upper atmosphere. A complex interplay between strong interactions and weak decays of the progeny of primary cosmic-ray particles created near the top of the atmosphere leads to the preponderance of muons observed in cosmic rays near the Earth's surface.

Of great practical importance to muon tomography is the rate at which cosmic rays "illuminate" objects which is quantified in terms of "muon

flux": the number of muons crossing a given horizontal area per second near the Earth's surface. At sea-level, the flux is about 200 cosmic-ray muons per square meter per second. Their average energies are sufficient to penetrate 20 m of water or 8 m of solid rock before stopping; many go much further. A typical muon will scatter by about 0.5° after traversing 4 m of rock. These key properties of naturally occurring cosmic-ray muons—flux, energy, and extent of scattering—largely determine the overall scope of the detectors needed for muon tomography.

Detecting and tracking cosmic-ray muons

Muons are detected and tracked by the contrail-like ionization they leave behind as they pass through matter. For his pyramid experiment, Alvarez used then state-of-art detectors somewhat over $3\ \text{m}^2$ in area that could track muons to 0.5° accuracy, sufficient to the task. Tons of other equipment needed to operate the detectors was hauled into the Belzoni Chamber via a narrow passageway, along with the tracking detectors. Advances in detector technology since the 1960s provide much cheaper and simpler options today. The active detector area needed for muon tomography, however, cannot be made much smaller with new technology because image quality depends on the number of muons detected, which is proportional to detector area.

Today's technologies involve rapid (few nanosecond) electronic sampling of ionization, with fine (millimeter to centimeter) spatial resolution in various media that can be assembled into the meter-scale particle tracking systems needed. Software algorithms associate ionization signals from each muon to determine the track direction and location. Parameters describing the track—two angles giving the muon's direction and two position coordinates—are stored for each muon detected for subsequent imaging processing.

The approach just outlined is followed in essentially every high-energy physics experiment conducted anywhere in the world today, including the immense detectors at the CERN Large Hadron Collider (LHC) now testing the Standard Model and searching for new phenomena. Fortunately,

detecting and tracking single cosmic-ray muons is vastly easier than reconstructing complex LHC collision events: there is only one particle to track at a time, and cosmic-ray track rates are a million times smaller than those encountered in LHC experiments.

Many choices go into the design of particle detectors. Briefly, the detectors built and tested as part of our University of Texas at Austin (UT) Maya Muon Project (Schreiner 2016), a collaboration between the UT Physics Department and the UT Center for Archaeological and Tropical Studies (Programme for Belize Archaeological Project 2016), emphasize: (1) ruggedness, to be able to operate reliably in remote locations; and (2) accuracy in tracking muons over a large angular field of view, for providing compact 3D imaging. Five detectors have been built and tested under various conditions, including an underwater calibration study. These detectors can be hand-carried and set up in various orientations in tight spaces, and operated without intervention for periods of days to months. We chose a cylindrical design, where the tracking sensors consist of three layers of 1 cm^2 cross-section plastic scintillator strips wrapped in helices on a 0.5 m diameter, 1.6 m long cylinder; the strips are sensed with optical fibers and photomultiplier amplifiers. An onboard computer determines the entrance and exit locations of muons passing through it, to an accuracy of a few millimeters. 448 scintillator strips in three cylindrical layers permit measurement of muon directions over essentially the entire open sky to better than 0.5° resolution, about the angular size of the moon. At sea-level, approximately 50 muons are recorded per second in each detector.

Four parameters—two direction angles and two position coordinates—describe each detected muon track. They are used to form an address for a large, four-dimensional array that records the muon flux in each of its 18 million cells. Our 4D track arrays can be thought of as being like pixels in a digital camera. The sizes of our “pixels” are comparable to the measurement accuracy—in direction and location—of the detector, when muon scattering is taken into account. Muon attenuation is measured by comparing numbers of muons recorded in the flux arrays for data taken with the detectors located next to a pyramid to runs recorded under a completely

open sky. Borrowing from astronomers, we describe such comparisons as “flat-fielding” the data.

To create images of muon attenuation or, equivalently, target mass density, the attenuation determined in each cell of the flux array is projected to 2D image planes of any desired size and orientation, using the track information encoded into the flux array address. Using detectors at several locations around the target to be imaged and methods of computed tomography, the 3D mass density is revealed.

The beauty of muon tomography is that track direction information, not available in conventional photography, allows examination of three-dimensional mass density projected conveniently onto two-dimensional image planes that can viewed and moved about by computer control to visualize dense regions and voids over the full volume of the target. No region of the target volume need ever be out of focus. Images from a laboratory test of cosmic-ray muon tomography are shown in Figure 1.

Additional considerations

Alvarez established practical and scientifically meaningful cosmic-ray muon tomography in the late 1960s at Chephren’s Second Pyramid. This success represented a major effort by a collaboration of experienced experimental physicists and archaeologists pursuing a clear research goal. Detector and computing capabilities have advanced substantially since then, including even an industrial base for muon imaging in specific kinds of national security applications.

Alvarez imaged Chephren’s Second Pyramid from the Belzoni Chamber, a room located near the center of the pyramid’s base connected by a horizontal tunnel to the outside. Aside from the convenience of having an existing tunnel under the site, there is no need to set up detectors directly under the space to be imaged. Given the relatively large spread in muon directions away from vertical, tracking detectors can be placed around the outside of the base of a structure of interest and still track muons passing through much of its volume, as indicated schematically in Figure 2.

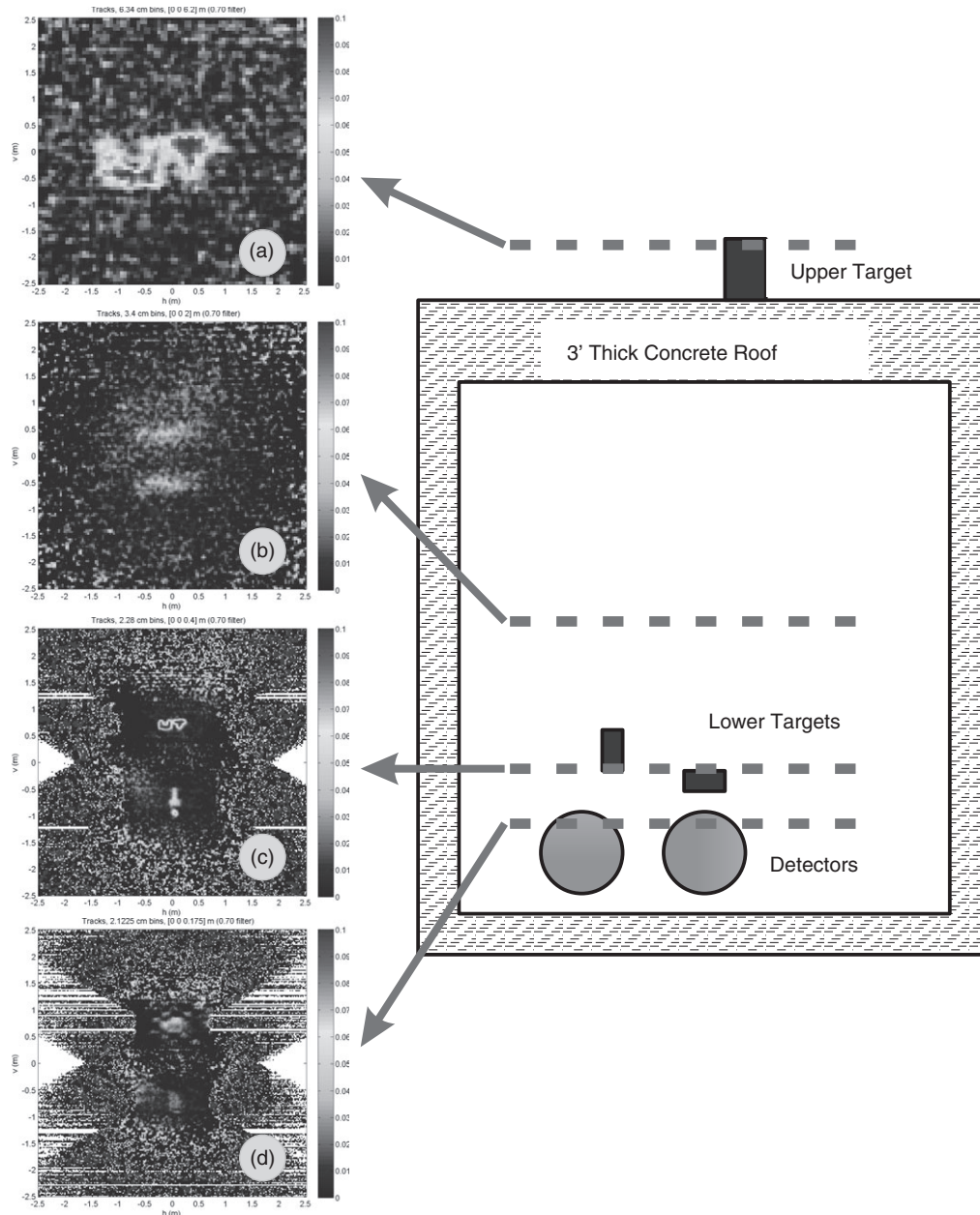


Figure 1 Laboratory test of muon imaging. Four reconstructed horizontal image planes are shown from a dataset taken with two UT Maya Muon detectors operating for roughly one week. The circles represent end views of the detectors used in this test. Arrows and dashed lines indicate the locations of the respective image planes. The top image (a) shows the pattern of bricks on the top of the building, 6 meters above the detectors and separated by 3 feet of dense concrete. Planes (b) and (d) show no distinct images; they are located in empty space between the two target sets and detectors. Plane (c) shows an image of two sets of lead bricks located just above the detectors. The ones spelling “UT” stand 8 inches high vertically; the faint T is only half as high, accounting for the smaller attenuation observed.

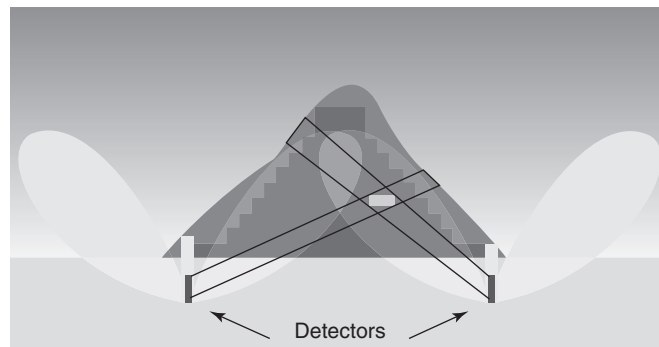


Figure 2 Schematic view of muon imaging by placing detectors around the base of the structure to be studied, when a tunnel underneath is impractical. The relatively broad angular range over which cosmic-ray muons are observed makes such a scheme feasible. The “mayfly” patterns above the detectors are meant to indicate the regions of highest sensitivity of UT Maya Muon detectors when deployed in a vertical orientation, as shown in Figure 3.



Figure 3 UT muon detector oriented vertically at the base of a Maya pyramid, “Structure 3”, at the Programme for Belize La Milpa archaeological site in Belize (Schreiner 2016). The shed protects the detector from rock fall. Note the umbrellas for scale.

The diversity in muon track directions needed to reconstruct 3D images can be achieved by operating several detectors simultaneously, as indicated in Figure 2, or by moving detectors sequentially to different locations and running over a longer calendar period, or any combination of the two. The setup of one UT Maya Muon detector adjacent to the base of a Maya pyramid at the La Milpa site in Belize is shown in Figure 3.

Finally, we note that muon tomography provides excellent opportunities for fruitful collaboration between diverse academic communities—physicists, archaeologists, and

anthropologists—as demonstrated by Alvarez, and taking place in a few universities today. Many physics departments have experts in particle detector systems, often with their own cosmic-ray test stands to explore new detector technologies right on campus. It is relatively simple to adapt such work to cosmic-ray muon tomography; a connection to archaeology can be a great attraction for students of both subjects to become involved. At the University of Texas at Austin, we have engaged several generations of students, with highly diverse interests, in the quest to build, deploy, and analyze data from practical detectors, based on modern technology that may teach us more about ancient societies.

The challenge today for emerging efforts in cosmic-ray muon tomography is to achieve the kind of definitive archaeological discovery that Alvarez and his colleagues produced nearly 50 years ago.

SEE ALSO: Computed Tomography; Electromagnetic Conductivity; Imaging; Neutron Radiography and Tomography; X-Ray Tomography

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Drones

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Drones, or unmanned aerial vehicles (UAVs), are commonly used to capture data from the air, providing a bird's-eye view of excavation areas, architecture, archaeological remains, and surrounding topography. In addition to aerial imagery, various sensors are used to gather data that can be used to create different kinds of maps and images useful in archaeological investigations. Due to their size, affordability, and portability, drones are ideal for archaeological mapping, and they are quickly replacing the need for aerial photography taken from satellites, airplanes, kites, or balloons. Moreover, while satellite imagery has the advantage of providing images of large tracts of land, it is often expensive and cannot provide the resolution that a drone, flown at low altitudes, can capture. Complementary to several other mapping methods, such as traditional surveying using a total station, drones can also cover more area in less time (Gutiérrez et al. 2016).

There are many different kinds of drones, but most can be categorized as either fixed-wing or rotary formats (Gutiérrez and Searcy 2016). Most are small and lightweight, and can carry payloads that fit the needs of the archaeologist. In addition to manual flight modes using a remote control, drones can be flown by autopilot software, allowing them to fly precise transects when collecting data on specific targets on the ground. Autopilot units with programmed flight paths use global positioning system (GPS) coordinates, and this requires that the drone continuously receives locational data from GPS satellites. UAVs using autopilot software are typically controlled by handheld devices, tablets, or computers.

Drones flown with digital cameras are capable of capturing high-resolution images at varying intervals. Post-flight processing of images is necessary and usually includes software capable of "stitching" together the photos to create a

seamless mosaic of images aligned with different coordinate systems (also known as orthomosaic imagery). While some drones are equipped with receivers that record GPS data for the images they capture, others require that ground control points (GCPs) be laid across a site. GPS data are then recorded for these GCPs using traditional GPS units, and these data are used to georeference the images, creating an orthomosaic that is georectified (Verhoeven et al. 2012).

Aerial images can be used to create several other types of images and maps through a process known as photogrammetry (see PHOTOGRAMMETRY AND STEREOPHOTOGRAMMETRY), which involves taking two-dimensional, overlapping photos through a process of triangulation to develop three-dimensional (3D) images (Chiabrando et al. 2011). Aerial photogrammetry provides data that can be used for 3D modeling of sites or architecture (Verhoeven 2011). 3D models are useful for the longitudinal study of site stability and conservation or in virtual reality modeling (see VIRTUAL REALITY MODELING) for educational purposes. Photogrammetry can also be used to develop digital elevation models (DEMs) and topographic maps. Digital surface models generated from aerial photos can be used for slope surface and landscape analysis.

In order to identify archaeological features and determine their spatial distribution, researchers from several institutions used drones to map portions of Easter Island (Rapa Nui, Chile), where the famous *moai* statues were sculpted and erected by people in the thirteenth century CE (Wechsler et al. 2016). Using fixed-wing UAVs, the team was able to create orthomosaic images of several areas on the island. Using existing GPS data from previous surveys on the ground, they were able to rectify feature locations, including rectangular stone platforms (*ahu*) where the *moai* were placed, as well as their large stone hats (*pukao*) made of red scoria. They also documented cultivation features like lithic mulch gardens and other house features. Due to the precision and high resolution of the aerial images, Wechsler et al. (2016, 38) were able to take incredibly accurate measurements of *moai* recorded in

the images. Compared to measurements on the ground, those taken from the aerial imagery were within one standard deviation (Wechsler et al. 2016, 38).

Aerial thermography has the ability to detect differences between “cool” versus “warm” features, which varies depending on the amount of heat retained by different soils and/or materials (Kvamme 2008). Infrared (IR) radiation cameras are mounted to drones to record thermal data, which can be used to produce thermographic images that potentially depict shallowly buried architecture (up to 50 cm) or other archaeological features (Casana et al. 2014). Thermal images can help detect features that are near the surface, even when covered with vegetation. Thermography has been found to be especially useful in detecting archaeological features and recent excavations where loose soils retain more moisture and less heat (Casana et al. 2017). In addition, different plants can create patterns in thermographic images, which correlate with specific features. Kvamme (2008) used aerial thermography at the Double Ditch site, an ancestral Mandan earthlodge village found on the Missouri River in North Dakota. He found that several “cool” anomalies were related to “open ditches, borrow pits, and house floor boundaries,” while “warm” anomalies often indicated “packed soil beneath trails, areas of mounded earth or thick village matrix” (Kvamme 2008, 77).

Light detection and ranging (see LIDAR DATA VISUALIZATION AND PROCESSING) (LiDAR) uses laser scanning to create 3D point cloud models of the ground surface and archaeological features. The large size of most LiDAR units has required that they be carried by manned aircraft, but smaller formats are available and can be mounted to UAVs. One of the major advantages of LiDAR is the ability to filter out any interference from vegetation, providing digital terrain models that can reveal archaeological features that lie beneath a forest canopy or thick vegetation.

On their own, the cartographic outputs reviewed above provide useful data for archaeological survey or mapping, but their utility is strengthened when combined with other remote sensing methods. These include ground-penetrating radar (GPR) (see VISUALIZATION OF GROUND-PENETRATING RADAR DATA), magnetic gradiometry (see MAGNETIC FIELD

GRADIENT), or electrical resistivity (see ELECTRICAL RESISTIVITY). Drones can also be used to take digital video of site excavations that are used for promotional or educational materials disseminated for the purpose of public outreach.

While there are several advantages to the use of drones, there are some caveats. Most small-format drones require batteries that are quickly depleted after short flight times and require recharging. The compact size of UAVs also makes them more susceptible to damage or crashes during adverse weather conditions like rain or high winds. There are unforeseen technical difficulties that can result in fly-aways, crashes, or erratic movements, common also to other pieces of electronic equipment used in typical archaeological field conditions. Finally, there are restrictions in some countries regarding where and how drones are flown.

The United States, in particular, has adopted rather strict rules regarding drones used in national airspace. For those flying UAVs for commercial or research purposes, these rules include flights no higher than 400 ft (122 m) above ground surface, maintaining line-of-sight during flight, restricting operation of drones to daylight hours, and flying only drones that weigh 55 lbs (25 kg) or less. The United States also requires that commercial drone pilots be certified by the Federal Aviation Administration, which includes passing an aeronautical knowledge test and registering and marking any UAVs used for business or research (Searcy 2016).

While the use of drones in archaeology is being widely adopted throughout the world, safety protocols and standardized methods have yet to be developed. Despite this fact, archaeologists using drones continue to find new applications as smaller sensors and more powerful photogrammetric software become available.

SEE ALSO: Aerial Photography; Airborne Remote Sensing; Digital Cartography; Digital Photogrammetry; IR Thermography

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Electrical Resistivity

ALEXIS MOJICA ABREGO

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Introduction

Until midway through the last century, the process of excavating the anthropic and natural stratigraphies sedimented at a certain site or excavation was the only approach that an archaeologist could use to detect buried archaeological features. During this same period, the electrical method was applied for the first time as a method of geophysical surveying to assess the archaeological potential of a given site. Although the basic concepts of this method were originally established by C. Schlumberger in field tests conducted in France in 1912, its use in the field of archaeology (see FIELD SURVEY) dates from the 1940s. The electrical method was initially developed for use in mining and to search for oil, but some years later it also began to increase in importance for the assessment of archaeological sites and for finding groundwater. The technological advances of the 1980s led to the development of geophysical devices that could quickly collect and store a large amount of data, as well as computational codes that could interpret the results more accurately. Currently, electrical prospecting devices can make continuous records via mobile systems, which in conjunction with GPS technology and statistical programs can generate very high-definition maps of the spatial distribution of the electrical properties of the soil. These advances have also been extended to other types of prospecting, which we will consider later. There is extensive literature on the potential of electrical methods for resolving archaeological problems, for example, Scollar et al. (1990), Clark

(2003), Campana and Piro (2008), and Schmidt (2013).

The concept of electrical resistivity

In general, the electrical prospecting method forms part of a series of electrical methods that use a source of artificial energy, and whose purpose is to detect surface effects generated by a flow of electrical current in the subsoil (Telford, Geldart, and Sheriff 1991). These effects are used to measure the apparent electrical resistivity of the subsoil, which is the basic physical parameter for electrical prospecting and other methods, measuring how difficult it is for a certain volume of soil to oppose the passage of moving electrical charges. What we mean by moving charges in the subsoil is electronic (ohmic) conduction, which is a normal mechanism that occurs in materials that contain free electrons. However, the propagation of charges may also be electrolytic or dielectric. Thus, the measured electrical resistivity depends on pressure and temperature, as well as on chemical phenomena in the medium in which the charges are moving (Nover 2005). Certain soil properties, such as its salinity, texture, humidity, organic carbon, pH, density, nitrate content, and type, are found to be closely associated with this physical parameter. Some very common cultural features, including streets, walls, floors, dumps, tombs, caves, and trenches, have different electrical resistivity values from the medium around them.

The apparent electrical resistivity value (ρ_a) is obtained using four metallic electrodes, or a quadrupole, inserted a few centimeters into the ground. The injection of a certain density of electrical current (i) into homogeneous soil via a pair of electrodes (C_1 and C_2 in Figure 1a) using an external power source generates a potential difference (ΔV) in the surrounding area that can be registered by the other pair of electrodes (P_1 and P_2 in Figure 1a).

Each apparent electrical resistivity value is obtained using the equation:

$$\rho_a = k \frac{\Delta V}{i}$$

and corresponds to a bulk value of a continuous volume of the subsoil beneath the quadrupole. Parameter k corresponds to a geometric factor associated with the position of the four electrodes, with the measurement unit of ρ_a thus being ohm.m, which is abbreviated as .m. At present, there is a range of electrode configurations or arrays adapted to certain research goals. The most widely used arrays in archaeology are dipole-dipole, Wenner, and pole-pole (see Figure 1b).

The layout of the equipotential and electrical current lines in Figure 1a is not representative of a real medium, as the current lines would refract in the interface between mediums; and as soil is a non-homogeneous medium, what we are measuring is not real electrical resistivity but rather an average known as the apparent electrical resistivity.

Electrical mapping and electrical resistivity tomography

In electrical prospecting, there are three modes of investigation, two of which are particularly widely used in archaeology: electrical mapping and electrical resistivity tomography. The third is electrical sounding, which is less common in archaeology but can be used to obtain important information about the vertical succession of the terrain (Dabas 1999). Electrical mapping consists of walking with a device over a series of parallel profiles spaced a short distance apart from each other and recording apparent electrical resistivity values at regular intervals. This methodology can be used to define a square or rectangle over the surface of interest with perpendicular x and y axes, each recording being associated with a metric coordinate (x, y) . Figure 2a shows the acquisition chart using a Wenner array.

This dataset (x, y, ρ_a) is then interpolated using statistical programs to generate a map of the spatial variations in apparent electrical resistivity at a fixed depth (which depends on the space

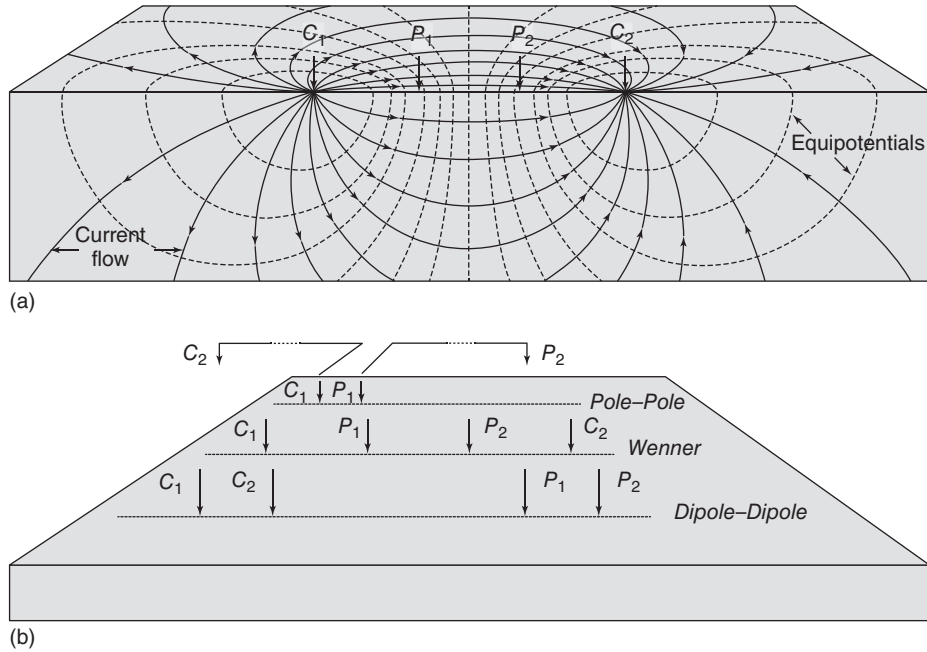


Figure 1 (a) Flow of electrical current and equipotential lines (of equal electrical potential) due to two point sources of electrical current C_1 and C_2 on the surface of a homogeneous site. (b) Most commonly used electrode arrays in archaeology.

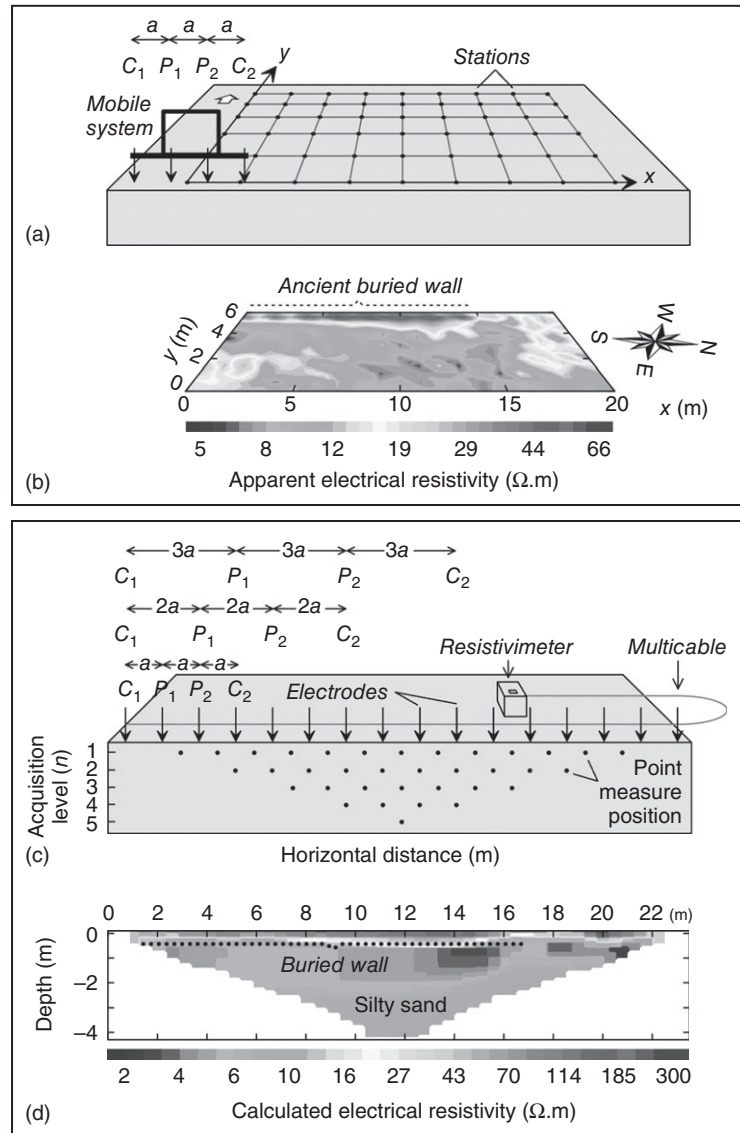


Figure 2 (a) Acquisition chart of apparent electrical resistivity values for electrical mapping using a mobile system with a Wenner array. (b) Map of apparent electrical resistivity, using Surfer 12 (of Golden Software) statistical program. (c) Acquisition chart of apparent electrical resistivity values along a profile using a resistivimeter, a multicable system connected to the electrodes, and a Wenner array. (d) Example of 2D electrical resistivity tomography obtained at a Hispanic archaeological site with a Wenner array.

between mobile electrodes) using logarithmic contour lines to make them easier to interpret. The presence of archaeological structures is revealed through the geometry of the electrical variations or anomalies that appear on the map. As an example of this methodology, Figure 2b shows a map of the logarithmic contours of the

apparent electrical resistivity at an archaeological site resulting from a dataset obtained using a Wenner array with a 1-m spacing between electrodes and 1 m between the six 20-m-long profiles. This map shows a strong linear anomaly of approximately 15 m length which was found to be associated with a buried Hispanic wall.

Due to the limited depth of electrical mapping, 2D electrical resistivity tomography is used, because it offers lateral and depth information. Figure 2c shows an apparent electrical resistivity data acquisition chart along a profile using a Wenner array. The multicable system connected to electrodes spaced at an equal distance (a) can provide considerably dense field data corresponding to multiple quadrupole combinations. Each of the apparent resistivity values obtained depends on a central quadrupole position (or the positions of each of the four electrodes) and on an

acquisition level n or electrode spacing, as shown in Figure 2c.

This dataset is subjected to a complex inversion process whereby a model of the subsoil is built through the definition of a series of rectangular prisms, for which the electrical resistivity values are calculated. This process is iteratively repeated until the difference between the measured and calculated electrical resistivity values is minimized. The result of this operation is a cross-section of the terrain that shows the real distribution of electrical resistivity in the

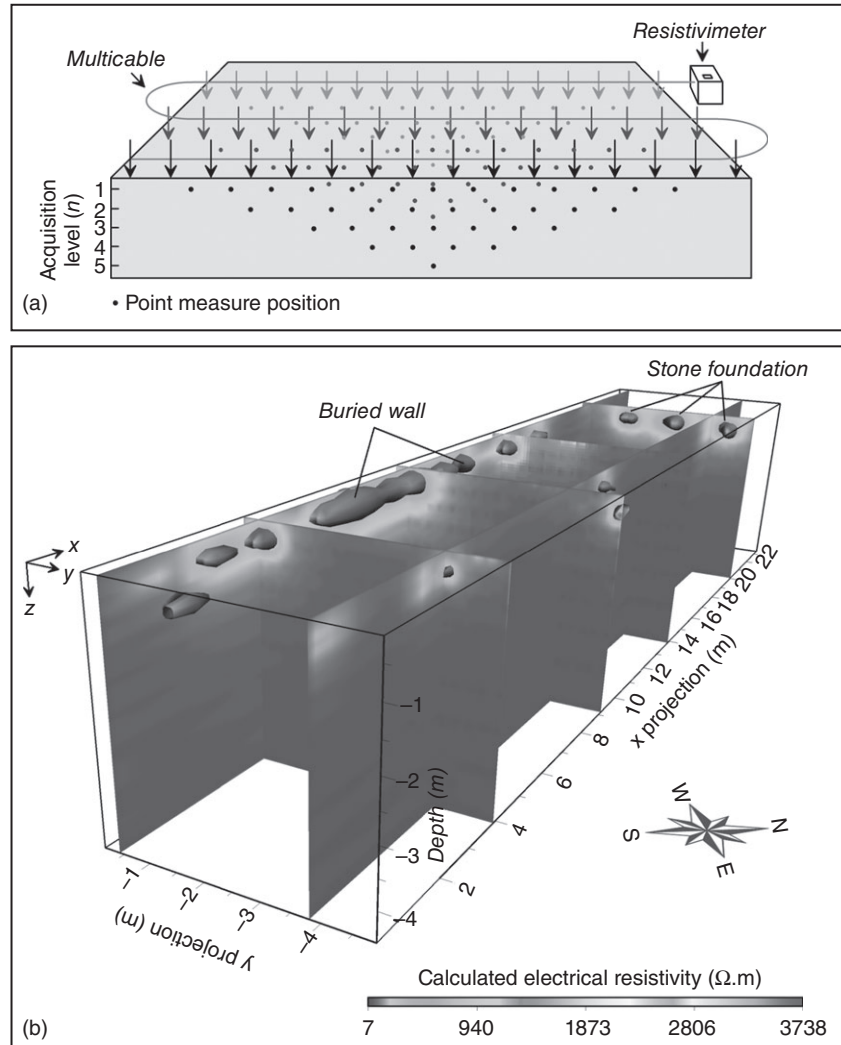


Figure 3 (a) Acquisition chart of apparent electrical resistivity values along several parallel profiles, and (b) example of 3D electrical resistivity tomography obtained at a Hispanic archaeological site.

subsoil at a given depth. Any electrical anomalies that appear are hence associated with the heterogeneities contained in the subsoil. Figure 2d shows the result of 2D electrical tomography obtained from processing a 360-item dataset using the Res2Dinv program (by Geotomo Software) over a 23.5-m profile with a Wenner array and an electrode spacing of 0.5 m. The lateral and depth extensions of two high electrical resistivity anomalies (>70 .m) can be seen, which are associated with the stone walls and foundations of a Hispanic site. At a greater depth, no anomalies associated with buried archaeological features can be distinguished.

Meanwhile, if we wish to obtain three-dimensional information, all we need to do is repeat the previous process over a certain number of parallel profiles. Figure 3a shows the data acquisition chart, and a detailed block of electrical anomalies, as a result of an inversion procedure using the EarthImager 3D program (of AGI Advanced) and Voxler 2 (of Golden Software) for a 3D representation, as shown in Figure 3b. The result is a three-dimensional representation using cross-sections and iso-surfaces for a set of electrical anomalies associated with the buried walls and stone foundations of a Hispanic convent.

Finally, the study of the electrical resistivity of the subsoil constitutes a powerful tool for non-invasive investigations of archaeological features buried at shallow depths. The contrast between the electrical resistivity values of these characteristics and the surrounding medium obtained in the high-resolution results provides an efficient alternative for the rapid evaluation of an archaeological site.

SEE ALSO: Visualization of Ground-Penetrating Radar Data; Visualization of Magnetometer Data; Visualization of Soil Resistance Data

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Electromagnetic Conductivity

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Electromagnetic (EM) conductivity is a geophysical method capable of mapping conductive archaeological features such as fortification ditches, moats, middens, and other features that retain moisture and therefore have higher conductivity than surrounding materials. It is also useful for providing geoarchaeological context to sites and landscapes, such as the locations of subsurface paleochannel deposits (Conyers et al. 2008). The property electrical conductivity (EC) is a measure of how well a material conducts electricity, and is the reciprocal of electrical resistivity (see ELECTRICAL RESISTIVITY) (ER), a property typically measured by injecting electrical currents into the ground by probe insertion. EM conductivity is measured by noncontacting electromagnetic induction (EMI), resulting in a weighted average of conductivity. As such, ER and EM conductivity are not directly reciprocal. Resistive targets such as rock walls are best detected by ER, while conductive targets such as fortification ditches are readily detected by EM conductivity. Archaeological features with relatively high amounts of organic material or finer-grained sediments such as silt and clay typically retain moisture and therefore have higher EM conductivity. Principal advantages of EMI are that it does not require contact with the soil and it simultaneously measures EM conductivity and magnetic susceptibility (see MAGNETIC SUSCEPTIBILITY) (MS), a property directly associated with human activity on the landscape.

History of electromagnetic conductivity in archaeology

All geophysical methods used in archaeology have their origins in geology or related disciplines, and

EMI is no exception. In general, archaeologists must adapt instruments and field methods for archaeological use, since geologists are typically looking for larger, more robust features. By the early 1960s, ER and magnetometry (see MAGNETOMETRY) had been successfully adapted and were part of standard practice in European archaeology. At this time, mathematical models showed that EM conductivity could be measured using magnetic dipoles much like those used in a metal detector (Scollar 1962, 152), but an early prototype instrument was found to respond primarily to magnetic properties (Tite and Mullins 1969). These difficulties were ultimately overcome in the 1970s, when Tite and Mullins (1970) determined that conductivity and MS responses can be separated by using specific frequencies and transmitter–receiver coil spacing. The first commercially available instrument, the EM31 Ground Conductivity Meter, was released by Geonics Limited (Ontario, Canada) in 1976.

Theory of operation

EM fields sent into the earth will behave in one of two ways depending on their frequency. High-frequency waves (10 MHz to 2.6 GHz) will propagate through the ground and produce reflections off buried interfaces. This is the basis of ground-penetrating radar (see GROUND-PENETRATING RADAR) (GPR), a method widely used in archaeology. At low frequencies (1–300 kHz), however, EM fields will diffuse through the earth, and in this process they are modified slightly, compared to those that travel through the air. EMI instruments measure how these induced fields change in response to the electrical and magnetic properties of the ground. The source EM field is generated by running an alternating current through a coil or loop, producing fields with wavelengths greater than 1,000 m. Figure 1 illustrates how this typically occurs. The primary EM field is generated from a transmitter and travels both above and below ground. Localized electrical currents called eddy currents are produced whenever the primary

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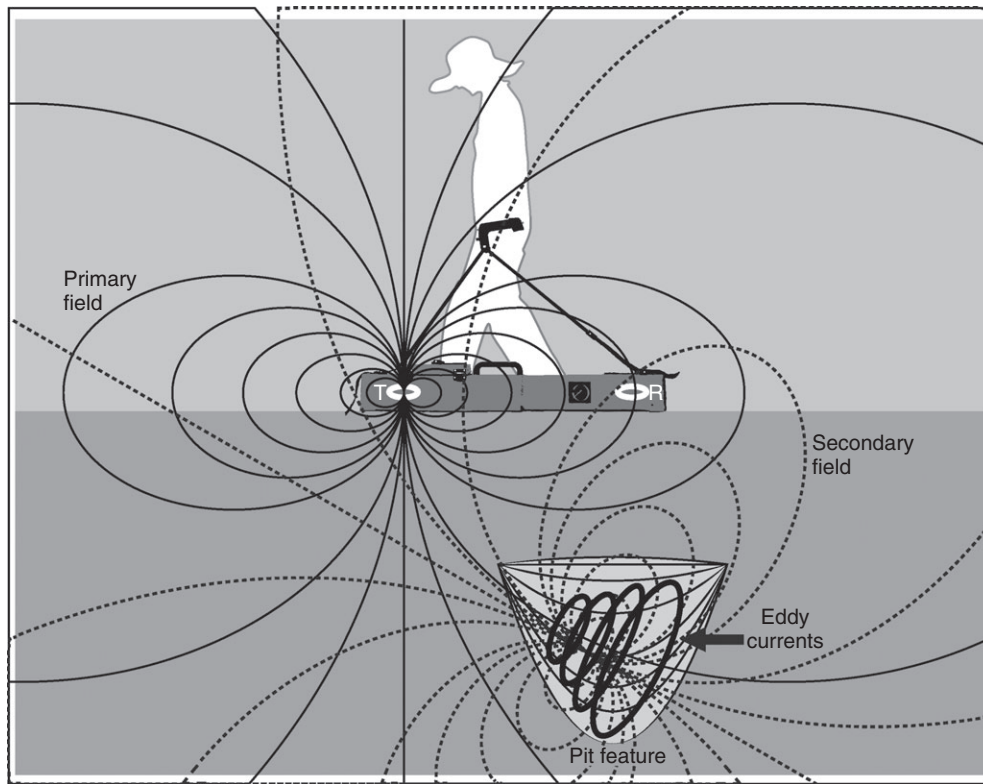


Figure 1 Generalized diagram of EM induction. A primary field is created by the transmitter (T) and extends outward in all directions. Conductive objects respond to the primary field by producing eddy currents, which in turn produce a secondary field. A receiver (R) measure the primary and secondary fields.

field encounters conductive features or layers. The eddy currents in turn generate a secondary EM field, and the receiver measures both the primary and secondary fields. The ratio of the secondary to the primary field is proportional to the EM conductivity of the ground.

The Slingram method

A variety of EMI systems are used in geology and other disciplines, but it is the Slingram method that is the most suitable for mapping archaeological and related landscape features. Slingram systems have transmitter and receiver coils, connected by a reference cable, typically mounted at a fixed distance on a boom, which is carried by a surveyor or towed on a sled. One of the most widely used in archaeology is the Geonics EM38 series (including the original EM38 and

the EM38DD, EM38B, and EM38-MK2 models), pictured in Figure 1. These instruments measure EM conductivity and MS at 1-m coil spacing, with the addition of a second receiver coil at 0.5 m on the MK2 model. This method of measurement is only possible when the ratio of the intercoil spacing divided by the skin depth (explained below) is much less than one, a condition known as “low induction numbers” (LIN) (McNeill 1980). Slingram EMI instruments are designed with this in mind, ensuring that frequency and distance between transmitter and receiver coils satisfy the LIN condition.

Depth and resolution

Slingram instruments can be configured in a variety of ways to target specific depths and optimize sensitivity to archaeological features. Depth is

dictated by coil separation and orientation. Most instruments have coils arranged parallel to each other, allowing them to be positioned horizontally or vertically during survey. Horizontal coils produce a vertical magnetic dipole, and vertical coils produce a horizontal magnetic dipole, with the former having a depth of investigation approximately twice that of the latter (McNeill 1980). An alternative coil arrangement places the receiver coil perpendicular to the transmitter. This arrangement improves sensitivity, but produces irregular anomalies that are not centered over their source, adding complexity to interpretation (Tabbagh 1986).

Maximum depth of investigation for EMI is known as skin depth, which is the depth at which response has decreased to 37 percent. Skin depth is irrelevant for Slingram instruments operating at LIN, however, because the depth sensitivity is controlled by weakening of the transmitted EM field as distance from the transmitter increases. Given that the transmitted EM field is elongated on the vertical dipole axis, depth sensitivity depends on the coil orientation. Figure 2 shows the relative response for vertical and horizontal magnetic dipoles as a function of depth. The horizontal magnetic dipole orientation is most sensitive to material near the sensor and the sensitivity decreases exponentially with distance away from it. Depth sensitivity for vertical magnetic dipoles is very limited at the surface, increases sharply to a peak sensitivity at a depth equal

to 40 percent of the intercoil spacing, and then falls off gradually. Thus, the vertical magnetic dipole orientations are quite insensitive to materials immediately beneath the sensor, but have a “sweet spot” of peak sensitivity not far below.

Given that the depth of investigation can be altered by coil configuration, spacing, and orientation, and that the instrument can be positioned at multiple heights above the ground surface, it follows that a single instrument can measure EM conductivity and MS at multiple depths. Several EMI instruments are configured with multiple transmitter–receiver pairs at varying coil configurations to allow up to four depths in a single pass (for example, the DualEM-21S, manufactured by Dualem, Ontario, Canada). Such multireceiver instruments are becoming the norm. It should be noted that there are also several multifrequency instruments that have been on the market for decades, which are designed to target multiple depths with a single, fixed-distance transmitter–receiver pair by broadcasting multiple frequencies. The theory behind EMI at LIN attests, however, that this is not possible at the range of frequencies and depths targeted for archaeology (McNeill 1996). Field tests show that changing the frequency of a fixed-coil instrument does not provide new information (Bonsall et al. 2013). These instruments can still collect useful data provided that an appropriate frequency is set based on the coil spacing, following McNeill’s (1980) LIN principles.

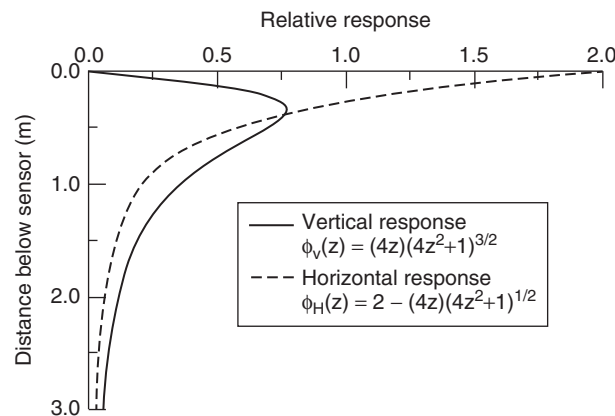


Figure 2 Relative conductivity responses for vertical and horizontal magnetic dipoles spaced 1 m apart as a function of depth.

Source: Adapted with permission from TN6 Figure 6 in McNeill, Geonics Limited (1980, 7).

Optimal use of electromagnetic conductivity

A principal disadvantage of EM conductivity when compared to ER is that it is less able to resolve highly resistive features, such as rock walls. This makes it a poor substitute for ER in many cases. EM conductivity data closely resemble ER when target features are conductive (Kvamme, Johnson, and Haley 2006, 253), and has a proven track record for mapping fortification ditch and moat features. Given that resistivity survey is slower and often impossible when contact resistance prevents its use, EM conductivity is a logical, though sometimes less ideal, choice. In addition, it makes sense to compare EM conductivity to GPR, since both methods respond principally to electrical properties. Like ER, GPR can more reliably resolve small features. Yet, EMI survey is often faster and less expensive, and may achieve a greater depth of investigation in conductive environments. In addition, interpretation of EM conductivity data is much less complex than GPR.

EMI survey has several advantages that make it an ideal choice in certain situations. First, EMI instruments measure not only EM conductivity but also MS, a statistically independent dataset that is often very useful for archaeology. Survey is fast compared to ER and GPR, and can simultaneously measure multiple depths. Finally, EM conductivity has been shown to be of particular utility in geoarchaeology, as it can simultaneously give detailed information about geological context such as paleochannels (Conyers et al. 2008) as well as large conductive features such as moats, fortification ditches, and middens.

At present, archaeogeophysics is experiencing a rapid increase in survey speed owing to the development of multisensor carts integrated with real-time global navigation satellite systems (GNSS). GPR array systems are now being used to map large areas with great speed and precision. This approach is growing in popularity, but is still cost-prohibitive for many. Magnetometer carts having four or more sensors are more affordable and now routinely used for reconnaissance. Smaller areas are then chosen based on these results for survey with slower, more traditional single-sensors such as GPR, EMI, and ER. The

use of EMI carts for landscape-scale survey is just now emerging as an alternative or complementary reconnaissance strategy. This approach offers the ability to map geological context from EM conductivity, and locations of intensified human activity from MS.

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Ethnography and Qualitative Methods in the Field

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Introduction

Archaeologists have used qualitative methods, and ethnography in particular, to enrich their understanding of past societies and human behavior since the advent of the discipline. Early efforts in American anthropology included ethnology and the collection of Native American artifacts under the assumption that Indigenous peoples were on the verge of being eradicated. In order to understand human cultural variation Franz Boas drew on cross-cultural comparisons and promoted a four-field approach to studying culture. His work on museum collections and material culture put sociocultural anthropology and anthropological archaeology into conversation with each other. By the mid-twentieth century, the formalization of anthropology as an academic discipline led to greater separation between the subdisciplines in order to establish methodological identities. For archaeologists, this meant a decreasing emphasis on qualitative methods to understand past societies.

One archaeological approach that continued to depend on qualitative data, however, was ethnoarchaeology—the study of contemporary material culture to construct models explaining archaeological patterns. In the 1970s Lewis Binford (1978) conducted ethnoarchaeology with the Nunamiut people in Alaska. Binford was interested in observing hunter-gatherer lifeways in periglacial environments in order to form hypotheses about material patterning observed at Mousterian archaeological sites. Among other

insights, Binford documented the seasonality of hunting and resource procurement, providing a model for archaeologists to test.

While ethnoarchaeology valued Indigenous knowledge systems about culture and the environment—in contrast to earlier arguments that deemed Native Americans incapable of the technological achievement clearly displayed in ancestral architecture and artifacts—many Native peoples found the ethnographic gaze exploitative. Archaeological and ethnographic studies were conducted without the consultation or participation from tribes, and the resulting information was limited to academic circles. Native Americans found themselves distanced from knowledge of their own ancestral past.

During the 1980s, archaeologists advocating a postprocessual perspective critiqued the positivist idea that archaeological knowledge could be purely objective and instead argued that interpretations were subjective and influenced by the positionality of the researcher (Hodder 1982). Postprocessual archaeologists called for an increased awareness of how interpretations about the past can be used to shape contemporary political agendas, nation building, Indigenous land claims, and heritage rights. In some instances they also used ethnographic research or invited ethnographers to study the politics and practices of specific archaeological projects. Marxist-inspired social archaeology emphasized the study of human diversity, focusing on minorities, women, children, the poor, the enslaved, and the disabled in the interpretation of archaeological evidence. In addition, social archaeologists argued for the importance of multivocality, which considers that there are different ways of knowing the past, and these ways can be interwoven through the coproduction of knowledge to create deeper understandings of archaeological evidence. These convictions inspired a turn towards qualitative methodologies.

In this entry a suite of qualitative methods are presented that archaeologists can use in their own field projects. Each project and sociocultural context is unique, and the qualitative tools outlined in

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this piece should stimulate discussion and creativity when it comes to understanding the past and making it relevant for the present.

Participant observation and interviews

Research participant interviews may be the most common qualitative method. The type of interview strategy chosen will depend on the research questions asked.

Structured and semi-structured interviews

Structured and semi-structured interviews are useful, as research participants are asked consistent sets of questions for the purposes of comparison. Structured interviews abide by a list of predetermined questions, while semi-structured interviews use an interview guide to maintain focus on key questions that address project themes.

Surveys or questionnaires

Questionnaires that address attitudes or opinions about history and heritage can also be used to collect high volumes of data efficiently. In Tahcabo, Yucatán, archaeologists working with the *Proyecto Arqueológico Colaborativo del Oriente de Yucatán* (PACOY) circulated a short survey questionnaire to households in different parts of the village to gauge interest in local heritage places, understand knowledge and use of the Yucatec Maya language, and identify the items and information people would like to see in a community heritage museum. The surveys helped researchers plan engagement activities with local students and design displays for the museum. Analysis of structured interviews and questionnaires can be both quantitative and qualitative.

Participant observation

For archaeologists interested in community archaeology or participatory research, participant observation is a crucial method for building rapport. For example, when first author Claire Novotny was starting a community archaeology

project in southern Belize, she went to a village and spent a month rotating between different family homes. Her participation in daily life—helping to cook meals, bathing in the river, attending soccer matches—demonstrated her intentions to work collaboratively with the village. She also met extensively with village leaders and had informal conversations with people about archaeology and heritage. That trip, while short by ethnographic standards, laid the foundation for a productive collaboration. Field notes and typed reflections provide important records of the research.

Oral histories and unstructured interviewing

During unstructured interviews, participants answer questions at their own pace and interviewers are flexible in the questions they ask, with space for the conversation to develop in unanticipated directions. In the case of oral histories, interviews are meant to elicit individuals to tell in-depth stories about their lives and the experiences of close family members. Unstructured interviews are useful during long-term field projects and are analyzed in qualitative ways.

Focus groups and community meetings

A focus group is a recruited group gathered for a structured discussion. Focus groups are convened by a moderator, who uses carefully chosen questions to guide the discussion. The goal of the session is to generate as many ideas or opinions as possible in a flexible group discussion setting. In the early stages of research, a charrette, which is a type of focus group, can be a useful method for joint decision-making. A charrette is a collaborative planning process that teams academics with local experts to accelerate research and ensure it is designed and disseminated appropriately (Roggema 2014). Another technique that uses focus groups is Photovoice (see below).

The community meeting is an important component of communicating with the public. Group meetings can be used to gauge community values and interest in archaeology, plan research designs, elicit research questions about the past, give feedback about research, or brainstorm for future

activities or projects. There are many guides online about how to conduct focus groups, charrettes, and community meetings. Community organizers and grassroots development groups have produced useful information that can assist archaeologists.

Participatory research

Participatory research is conducted in partnership with communities: it is conducted *with* rather than *on* research participants. Participatory research can encompass one element of a project or constitute the design of the project in its entirety. Community partners participate in all phases of a truly collaborative project, from design through interpretation and publication. Scholars conducting research in a participatory way strive to democratize knowledge production by working with communities to identify local needs relevant to research questions as well as opportunities for meaningful action and dialogue. All the qualitative methods described above could be used to conduct participatory research, but group methods such as focus groups may be the most appropriate for incorporating a wide range of local perspectives and taking into account the power structures at play (Pollack 2003).

Participatory archaeological research empowers communities to reclaim their histories, while providing opportunities to understand them better. The Market Street Chinatown Archaeological Project is one example of collaborative research developed as a partnership among academics, cultural resource experts, and the Chinese descendant community. In this case, the local Chinese American population helped to develop new research questions (Voss 2005: 434) as well as exhibits and educational programs. Atalay (2012) has written about archaeological projects that adhered to the standards of community-based participatory research (CBPR), a term that originated in the field of public health. All five projects discussed in her book brought reciprocal benefits to the partners involved and acknowledged the value of bringing together diverse knowledge systems.

One strength of implementing CBPR is the coproduction of knowledge; research questions

and agendas are generated by local communities in partnership with researchers. Democratizing the process of knowledge production addresses power imbalances in archaeology (and the social sciences more broadly) in which researchers control and restrict access to data, interpretation, and results. When communities take part in setting priorities and guiding the research process, the resulting knowledge can be controlled by and serve the needs of community members. Additionally, participants can contribute their expert knowledge about their communities to the research, providing a more holistic rendering of history. The democratization of knowledge production about the past empowers communities to make decisions about their heritage, while also strengthening research outcomes.

Record keeping and transcriptions

The seemingly simple act of taking notes frames archaeological interpretations and ethnographic interactions and can privilege some voices and ways of knowing over others. Recent scholarship has highlighted the ways in which new technologies allow for more systematic categorization and recording of the qualities rather than just quantities of archaeological data. These include opportunities for archaeologists in the field to make more culturally relevant observations of the matrix textures and artifacts that they encounter (Jackson, Motz, and Brown 2016).

Ethnographic note-taking, audio recording, and transcription

Ethnographic research depends on accurate note-taking. Some notes occur in the field as memory devices, while more thorough note-taking occurs later. Besides description, notes should include reflection, new questions, and emerging themes. Audio or video recording will also prove critical for future observations about the nuances of an interview or focus group. Transcription is an important part of the analysis process—typing up the script of what was said provides an opportunity to hear the information in new ways. Software exists to facilitate transcription; for example, one can change the audio

file speed, add timestamps, and access shortcut keys that simplify the process (e.g., f4transkript; Express Scribe). Next, some researchers apply codes to transcripts either freehand or using analysis software (e.g., Atlas.ti). This can help researchers to track themes that came up during the research and even model the connections between data points.

Institutional Review Boards (IRB) and consent

The Institutional Review Board (IRB) process was designed for the health research sector, but can prove useful to archaeologists engaged in ethnographic research as a technique to think through possible research risks and benefits. All of the above-mentioned methods, due to the participation of human subjects, must be approved or deemed exempt from the process of review by the principal investigator's IRB, based at their university. While funding agencies often require receipt of IRB approval or exemption, it is the responsibility of the researcher to pursue the review process, whether or not it is common practice in the host country. In accordance with IRB standards of ethics as well as those of professional organizations, consent must be obtained from any research participants or informants. The IRB offices at some universities have pioneered alternative ethics trainings for individuals who do not have easy access to computers or who do not read at a high level of proficiency, which can be important for projects in which local residents participate in the analysis of ethnographic data. All research team members should be trained in human research ethics.

Social media and mixed media

Public archaeology projects often use technology and social media to share knowledge with interested parties. Blogs have been a common tool used to share the processes and discoveries of archaeological excavation, laboratory analysis, and interpretation. In some cases, the goal is to expand the geographical spread of archaeological information and teaching resources, while in other cases, online tools allow for deeper local

engagement with the archaeological project. Online publications are broadening the audience for digital media related to anthropology and archaeology through high standards of journalism and the availability of multiple transmission formats including photo essays, which are commonly too expensive for print media (e.g., SAPI-ENS, www.sapiens.org). Digital servers also offer platforms to share data among scholars, including open-access archives, articles, and journals.

Other valuable examples of mixed media efforts include performance ethnography, participatory filmmaking, and Photovoice. Photovoice is a problem-based technique that uses photographs taken by community members as the basis for discussion and action related to local needs. The main goals of Photovoice as described by Wang and Burris (1997) are: (1) to identify community strengths and challenges, (2) to promote dialogue of important issues through discussion of photographs, and (3) to create change. This method can be an efficient mechanism to assess community values and to consider ways in which an archaeological project can contribute to the place where it is based. The process of Photovoice involves several meetings with a small group of participants, each of whom receives a disposable or digital camera. During the first meeting, facilitators describe the project, obtain consent, and receive training in photographic skills, and the group as a whole decides on the question to be considered through photography in the coming week. In subsequent sessions, in-depth discussion of photos takes place, leading to an analysis of the problem and the development of action steps. Transcripts of the discussions are distributed to participants and studied collaboratively. For an example of an archaeological application of Photovoice, see Dedrick (2018).

Ethnohistory

Ethnohistory is grounded in the collection and analysis of ethnographic and historical data, and has proved incredibly useful in historical archaeology. It extends the analysis of historical documents to include materials such as maps, folklore and oral histories, traditional knowledge, archaeological artifacts, museum collections,

and artwork. The goal of ethnohistory is to understand the history of a cultural group on its own terms; this is especially useful for Indigenous peoples, whose histories have been recorded and distilled through a Western lens.

An excellent example of ethnohistory is the San Pedro Valley Ethnohistory Project in southern Arizona. The project blended ethnographic, historical, and archaeological information to gain a deeper understanding of how Native Americans have related to the San Pedro River Valley over time. From 2001–03, team members collaborated with the Hopi, Zuni, Tohono O'odham, and San Carlos and White Mountain Apache tribes to investigate themes of social identity, migration, warfare, subsistence ecology, and population density in the San Pedro Valley (Ferguson and Colwell-Chanthaphonh 2006: 6). Fieldwork included archaeological site visits, museum research, and interviews. Conversations and reflections from the field were starting points for later semi-structured interviews with participants (Ferguson and Colwell-Chanthaphonh 2006: 19). Taking into account how material culture, language, and oral traditions interweave to form historical narratives contributes a humanistic view of the past and reaches towards equitable conservation and management of heritage resources.

Future directions

Qualitative methodologies provide avenues for collaboration with stakeholders as well as ways to gauge the salience of research projects for the public. Employing qualitative methods in archaeological contexts spurs innovation and creativity. For example, the field of digital humanities is emerging as an endeavor through which archaeologists can visualize and present material culture and qualitative data (Berry 2012). Digitization of archaeological and heritage-related materials, including texts, images, and audio-visual materials, mediate the ways in which researchers and stakeholders can analyze and consume archaeological knowledge.

SEE ALSO: Archaeology; Archaeology and the Present; Community Heritage; Designing and Co-Creating Heritage; Digital Media in

Archaeology; Ethnoarchaeology; Heritage and Community Archaeology; Heritage and Ecomuseums; Heritage Ethics; Heritage Management; Heritage Planning and Design; Public Archaeology

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Field Survey

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As many kinds of archaeological research demand information at the scale of regions or landscapes rather than individual sites, field survey has been integral to archaeology since the pioneering antiquarian reconnaissances of the nineteenth century. It has developed into a suite of methods that help archaeologists to sample the archaeological resources of a region, to maximize the probability of discovering a particular site or kind of site, to understand ancient landscapes, settlement and land-use systems, and communication networks, and to minimize the probability that development projects will damage significant archaeological resources (see ASSESSMENT: HERITAGE IMPACT (HIA)). Each archaeological objective and field context calls for a different approach to survey design. Whether the objective of the survey is simply to find sites, to learn about the spatial distribution of sites or artifacts, or to estimate the parameters of some population of sites or artifacts, what this object is should have a particularly important impact on the survey strategy.

Broadly speaking, surveys fall into two major classes (Banning 2002). Surveys whose main purpose is to search for a particular “target” or class of targets constitute prospection; surveys meant to yield a representative sample of a landscape or the archaeological resources in that landscape may be called sample surveys (see SAMPLING THEORY). In addition, we may further distinguish surveys on the basis of the way in which the survey effort is distributed and the methods used to detect archaeological remains.

A targeted or purposive survey invests survey effort intensively in the spaces most likely to contain the archaeological evidence of interest, typically by using a predictive model in a geographic information system (GIS; see PREDICTIVE MODELING) with reference to geoarchaeological evidence, and consequently is

prominent in prospection. Sampling surveys typically begin by formally subdividing the region of interest into either geometric (typically square) or more natural or convenient spatial units and then sampling these units either randomly or systematically, or surveying all the spatial units evenly, through what archaeologists often call a “full-coverage survey.” However, that term is somewhat misleading in its implication that it results in a full inventory of archaeological remains, as the extent to which full-coverage surveys represent all the sites accurately depends on intensity or amount of effort devoted per unit of space.

Surveys also vary in their methods of detection. The most common types of survey involve fieldwalking: teams of archaeologists walk through fields, preferably after plowing and disking, or through pasturelands, preferably when vegetation is sparse, and examine the ground in their path, searching for artifacts that are visible on the modern surface to their unaided eyes. Because archaeological remains are often buried or their surface visibility is poor, however, this method is only very effective when sites are shallow and the topsoil is thin, plowed, or disturbed. In areas of poor visibility, such as forests, or where artifacts are likely to be deep, as in alluvial or colluvial contexts, it is often necessary to use either intrusive methods, for example, shovel testing, trenching, coring, and augering, or remote sensing, for example the ground-penetrating radar (GPR), the magnetic or electromagnetic survey, or aerial reconnaissance for “crop marks”—that is, the traces of buried walls and ditches that are visible in the color and height variations of plant cover. However, most of the alternatives to fieldwalking are more costly and their probability of discovering sites or artifacts of interest depends greatly on the spacing of observations and on the degree of contrast between archaeological features or artifacts and the sediments in which they occur.

This brings us to the suite of factors that affect survey results, and especially the probability that a detector (including human eyes) will successfully detect and recognize an archaeological

target. One of these factors, already mentioned, is visibility, which is the degree to which the target “stands out” from its surroundings and depends a great deal on such things as vegetation cover, presence of natural stones that could be confused with artifacts, soil moisture (in the case of crop marks and resistivity survey), and even weather and light conditions. Another factor, often called obtrusiveness, has to do with the characteristics of the target itself, such as the size of a site and whether or not it has a mound or architecture, the magnetic susceptibility of a feature, or the color and reflectivity of a potsherd (Schiffer, Sullivan, and Klinger 1978). However, these characteristics still need to be evaluated in the context of visibility, as a brightly colored sherd, for example, is easier to detect visually on a bland background of contrasting color than on a diversely or similarly colored background. Another important factor is intensity, or the density of the search effort; obviously, devoting more time to searching a given space, or spacing shovel tests or fieldwalking transects more closely, yields a higher probability of detecting things than would a faster or less dense search (Krakker, Shott, and Welch 1983; Plog, Plog, and Wait 1978). The geometry of search grids also has a tremendous impact on the probability of finding sites or clusters of artifacts (Plog, Plog, and Wait 1978; Verhagen and Borsboom 2009). Finally, many aspects of the detector (including the human detector) are relevant to survey results; both people and instruments vary in their abilities and are never perfect (Banning, Hawkins, and Stewart 2011; Plog et al. 1978).

Evaluating surveys and survey design

Inevitable variations in all these factors can make it difficult to compare surveys, or even to be confident, in the case of heritage management, that the survey will have discovered all the significant archeological remains that may exist in the space under survey. Consequently, we should evaluate surveys both during and after their implementation, as a quality assurance practice (Banning 2002; Banning et al. 2016). These evaluations allow us both to make more realistic use of the survey data and to design more optimal surveys.

We can evaluate those aspects of a survey that concern the effectiveness of detection with the aid of search theory (Koopman 1980; Stone 1975). One kind of function describes the relationship of search effort to the probability of discovery; another describes the way in which discovery probability declines with range away from the detector (be that an instrument or the fieldwalker’s eyes).

Whether we measure the search effort as the amount of time devoted to searching a space, as the total length of all search paths across the space, or as the total area of shovel tests or auger holes dug into the space, the search effort function is nonlinear. Specifically, the probability of discovery increases with the effort, but the slope of the relationship declines, so that the curve begins to level off. This happens for a variety of reasons, including that the number of detectable targets is finite and that continued survey will sometimes be redundant. This relationship has implications for how much survey we should devote to a space before it makes more sense to move on to some other space.

The function that describes the relationship of range to discovery probability is typically S-shaped, with fairly high probabilities of detection close to the surveyor’s path that at first decline rapidly with distance before levelling out into a long tail of values approaching a probability of 0, much like a normal distribution centered on the search path. We can estimate range functions under a variety of conditions and detectors by experiment (Banning et al. 2011; Banning et al. 2016).

Once we can estimate a range function for a particular context (combination of artifact type, visibility, and crew abilities, for example), we can use it to estimate a “sweep width” (Banning et al. 2011). Whether by fieldwalking or some other method, sweep width is double the range within which the number of artifacts we fail to discover is equal to the number of those we do discover outside that range. Consequently, it is the width within which we find as many artifacts as we would have found, had detection been perfect within, but zero outside, that width. Multiplying sweep width by the total length of paths walked within a space produces the “area swept,” and dividing the area swept by the area of the space being surveyed measures “coverage,” one of the

most useful measures of survey thoroughness. Although 100 percent coverage would be ideal, it is often far too costly; but it makes sense to know what a survey's coverage was if we are to interpret its results accurately.

We can use the information from evaluation to optimize surveys for our primary goals. For example, when it is extremely important for a survey not to miss particular kinds of artifacts (in other words, to have nearly 100 percent coverage for that type of artifact), we can use estimated sweep width to establish the spacing between surveyors that will accomplish this. Since it is not uncommon for sweep widths to be smaller than 2 m, this could result in very costly surveys, but we can also use sweep widths to balance cost with coverage, potentially deciding, for example, to compromise at 30 percent or 50 percent coverage for artifacts, acknowledging that coverage for large sites could be close to 100 percent while coverage for very small ones might be very much lower.

Technologies for field survey

To date, the most common method for archaeological survey is still fieldwalking, which has been the focus of most of the discussion above; and it is supplemented by subsurface testing through shovelling, trenching, augering, or coring (see AUGERING and CORING). However, other technologies for detecting the distribution of archaeological resources on landscapes are increasingly important.

Many of these technologies involve remote sensing, either from aircraft or from satellites. The imagery from aircraft has been important since the 1920s and still tends to have the advantages of high resolution and, in some cases at least, historical depth (see AERIAL PHOTOGRAPHY and AIRBORNE LASER SCANNING AND LIDAR). In regions where there has been considerable development recently, for example, old aerial imagery from the 1920s to the 1970s can often reveal traces of archaeological sites that have since suffered destruction, major degradation, or reductions in visibility. The gradual declassification of more recent satellite imagery means that this class of data is approaching the resolution

of the aerial photographs while also, in many cases, providing data outside the visual spectrum. Space-based radar or LiDAR has been particularly helpful to archaeologists, allowing for example the identification of Mayan structures that would be obscured by vegetation in more conventional aerial photography, as vegetation is transparent to radar.

Many ground-based remote-sensing methods for detecting buried features and artifacts have been available for more than half a century but, for practical and budgetary reasons, remain restricted in their application. Magnetometry (see MAGNETOMETRY), electrical resistivity survey, electromagnetic survey, and ground-penetrating radar can all be highly effective in some contexts for detecting buried walls, ditches, and other features, and sometimes large or highly obtrusive artifacts, but tend to require very closely spaced observations and generally work better in areas where we already know that there is a site of interest. It remains rare for these methods to be used for the discovery, rather than the evaluation and interpretation, of sites.

In some regions of the world, artifacts are rare or poorly preserved, and sites are effectively invisible to most of the methods mentioned above. This is particularly true in some tropical regions, where acidic soils have corroded away most traces of ancient activity. However, chemical traces can persist and, in these regions (and elsewhere), one strategy is to search for sites by their chemical signatures (see CHEMICAL MAPPING). Places where humans have deposited considerable amounts of organic trash can have elevated levels of nitrogen and phosphates (see SOIL PHOSPHATE CHEMISTRY and SOIL SURVEY), so analyzing soil samples taken over a grid of locations can sometimes identify settlement sites. These types of survey have recently benefitted from the availability of portable X-ray fluorescence analyzers (pXRF; see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF) and X-RAY FLUORESCENCE SPECTROMETRY (XRF)), which allow fast results while still in the field, so one does not have to wait for lab analyses after each field season.

Underwater and intertidal surveys are also special cases. While survey in intertidal zones (between high and low tides) can use many of the same methods as terrestrial fieldwalking, tides and their effects on the time available for

fieldwork and on the visibility and distribution of archaeological remains in this zone can be quite challenging. Underwater survey is especially challenging, because visibility tends to be very poor and the amount of time for which divers are able to stay down can be very limited. However, such surveys, especially when targeted through some combination of predictive modeling, boat-based sampling, and remote sensing (see SONAR AND SIDESCAN SONAR), can be extremely useful for identifying archaeological evidence of coastal occupations during periods of low sea level, such as the early Holocene, not to mention the survey for shipwrecks.

SEE ALSO: Cultural Resources Management; Heritage and Landscapes; Mobile Geographic Information Systems (MGIS); Urban Environments

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Geomorphological Survey

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Because of its value for understanding the evolution of landscapes related to past human activities, as well as for interpreting environmental contexts (see ENVIRONMENT AND LANDSCAPE) and the dynamics of site formational processes (see FORMATION PROCESSES), the geomorphological survey is an essential field method in archaeology. The major dimensions and goals of a geomorphological survey are to identify and document (a) the types of landforms within a landscape, (b) the processes that have led to their formation, and (c) the long-term changes in the landscape. The geomorphologic survey is thus focused on both process and product; it is concerned with inferring the dynamics of landscape change as reflected in sediments, stratigraphic sequences, and landforms at a variety of spatial and temporal scales. The results of a geomorphic survey are essential to the successful interpretation of the archaeological record, providing the opportunity to examine and gain a clearer understanding of the natural and human (anthropic) processes that contributed to the evolution of the landscape. Because both natural processes and human activities can contribute to the formation of a landscape, an interdisciplinary approach that integrates the geomorphological survey is critically important to any archaeological field study (see FIELD SURVEY); it is part of the geoarchaeological (see GEOARCHAEOLOGY) approach to archaeological interpretation and also environmental archaeology (see ENVIRONMENTAL ARCHAEOLOGY).

The integration of the geomorphological survey in archaeological studies and investigations of human–environment interactions at the landscape-scale has evolved since the late 1800s when John Wesley Powell incorporated landscape dynamics and land-use in his research. During the early 1900s O. G. S. Crawford used aerial photography to place archaeological sites within

the context of broader landscapes in Britain. Raphael Pumpelly conducted a landscape study in Turkestan related to the origins and growth of the Anau civilizations, while William Morris Davis and Ellworth Huntington studied the geomorphic evidence for a series of glacial-interglacial episodes that documented regional Quaternary climate and environmental change in the region. During the 1920s and 1930s Elinor Wight Gardner conducted geomorphic surveys in the Western Desert of Egypt in the Fayum and Kharga Oasis. Carl Sauer developed an approach that viewed landscape as a product of space, time, and natural and human processes, and Kirk Bryan played a prominent role in applying geomorphical survey to the investigation of Quaternary landscapes in North America. In 1940s, Herbert E. Wright, Jr. conducted geomorphological studies in the Near East at Ksar Akil and Jarmo.

In the 1950s Fred Wendorf and John Miller applied a landscape approach to study the relationships between alluvial terraces and Pueblo sites in New Mexico, Sheldon Judson conducted a geomorphic study linked to Paleolithic sites in the Dordogne region of France, and Karl Butzer mapped surficial deposits related to archaeological sites in the Nile Valley. Field studies conducted by Chris Kraft, Stan Aschenbrenner, and George Rapp in the 1970s focused on the paleogeography of the coastal plain of Greece. Bruce Gladfelter (1977) advocated a geomorphic approach that emphasized the depositional context at site-specific location, local landscape (habitat), and regional scales.

The importance of the geomorphic survey in archaeology is that it is a way to develop a clearer understanding of the natural and human processes that have produced the landscape context (Butzer 1982). The landscape context can be defined at the level of a regional ecosystem consisting of the landforms and topographic setting of the area. The geomorphic survey is also concerned with the sequence of events recorded by the individual sedimentary sequences and evaluating these local physical sequences in terms of the broader regional-scale landscape history.

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It involves understanding the erosional (see *EROSION*), depositional, and soil forming events that create the present-day landscape; these are the landscape-scale formation-processes associated with the destruction, transformation, and preservation of the archaeological record (see *FORMATION PROCESSES*). The geomorphological survey also is valuable in providing a temporal context, correlating sites and related deposits, predicting and explaining site location, and evaluating the potential site restructuring. In general, the geomorphological survey provides information on both the spatial and temporal contexts at multiple scales.

The primary objective of the geomorphological survey is to document the features of the present-day landscape and evaluate the processes and dynamic components that have actively transformed the landscape over time. Because the landscape can be considered a product of alternating periods of erosion, deposition, and stability, different conditions may prevail and be associated with specific, contemporaneous landforms. While the geomorphological survey is focused on landscape-scale studies, the scales of study can range from regional mapping to detailed studies of sedimentary sequences and individual deposits. Regional and site-specific scale archaeological interpretations can be strongly influenced by the dynamic processes involved in landscape evolution and the geomorphological survey should be an integral part of any archaeological field study.

At a minimum, the geomorphological survey should result in a map showing the spatial distribution of landforms and the map should be accompanied by a detailed description of the sediments that compose the landform. Thus, a key objective of a geomorphological survey is a surficial geology map, typically showing the distribution of late Cenozoic strata and sediments. A geomorphologic map of the landscape is based on the spatial extent and relationships of landforms, as well as the compositional characteristics and ages of the sedimentary deposits. These kinds of maps are typically initially developed using aerial photographs, satellite images, and existing topographic maps as a basis for extensive field studies. The maps categorize the various geomorphic units (such as alluvial fans, floodplains, terraces) and provide a means of documenting

the processes involved in their formation. To be relevant to the archaeologist, the geomorphologic information must be related to the archaeological materials found on or within the sedimentary deposits that compose the landforms.

Preliminary regional-scale methods of mapping employ satellite imagery (see *RADAR*) and aerial photographs (see *AERIAL PHOTOGRAPHY*) as well as available topographic maps and DEMs (digital elevation models). Topographic maps are also essential; they provide more than just elevational data and may need to be at customized scales. Geologic maps are useful, as are soil survey maps (see *SOIL SURVEY*).

While preliminary mapping plays an important role, the geomorphological survey is fundamentally a field-based approach. It is in the field that the ground-truth testing of the preliminary mapping is conducted and where direct observations are made and data are collected. Typically, at the preliminary stage the geomorphic surfaces are mapped using available topographic maps or aerial photographs and these interpretations are then field-checked. The field check can be based on natural exposures or deliberately excavated stratigraphic trenches, or cores. In the field, the objective of the geomorphological survey includes the observation and description of stratigraphic sequences. Besides using stratigraphic profiles available from archaeological excavations, the geomorphological survey will examine natural exposures or conduct additional coring and trenching. To collect detailed information regarding the lateral extent, depth, and composition of landforms, field techniques such as description of natural exposures or outcrops, or augering (see *AUGERING*), coring (see *CORING*), manual trenching, or excavation by machine are applied. These techniques provide important details about the deposits themselves (boundary characteristics, texture, composition, structure, presence or absence of artifacts and fossils). Field descriptions of sediments and soils provide a way to document and describe the stratigraphic sequences and these descriptions are used to infer the processes of deposition and soil formation. Once exposures have been described, samples may be collected for further physical or chronometric analysis (see *DATING CERAMICS AND LUMINESCENCE*).

While most geomorphological surveys apply a multi-scalar approach to investigating the evolution of landscapes, as an archaeological field method the geomorphological survey has as a primary objective the creation of a surficial geology map that can provide the basis for archaeological sampling and explanation. As part of this surficial geological map, the landscape is subdivided into geomorphic zones, or landforms. Morphostratigraphic units for surficial studies are identified or described based on surface form and not necessarily based on distinctive lithologies. Typically morphostratigraphic mapping will include defining surfaces that are indicative of an erosional or depositional process and are defined by both the processes of formation and the sediments. For example, a geomorphic survey along the Big Fork River in northern Minnesota used aerial photographs and topographic maps to develop a model of the surfaces and sedimentary deposits associated with Archaic and later Holocene archaeological occurrences, which were further investigated by field excavation and coring as well as detailed laboratory sedimentological analyses (Hill, Rapp, and Jing 2011). The ultimate product from this type of study is a map that documents the surface type and relative position of landforms within a landscape. One approach to integrating surface morphology with the sedimentary sequences within the landforms is by defining mappable bodies of sediment as allostratigraphic units. This type of classification requires field description recognition of the boundaries. A key objective is establishing the age relationships or sequence of landforms. The bounding discontinuities for allostratigraphic sequences can be erosional disconformities, soils, or landform surfaces.

In terms of archaeological goals and questions, the geomorphological survey is especially crucial in attempts to infer the environments and natural resources related to human presence on a landscape, predicting the location of archaeological entities, estimating the age of deposits containing artifacts, documenting the stratigraphic and landscape contexts related to the archaeological record, identifying and describing site matrix and evaluating events of site formation particularly those resulting from geologic restructuring. Thus, the geomorphic survey provides a way of not only predicting the locations of buried

preserved archaeological remains, it can also contribute to understanding what processes may have restructured the original spatial and compositional characteristics of human activity. These processes include surficial rearrangements (such as by running water), weathering, and burial (see TAPHONOMY).

Because the geomorphological survey can result in a well-defined spatial and temporal framework for the landscape under study, it is useful in archaeological site modeling and prediction, and testing. Site predictions, especially buried site prediction models, typically involve the integration of geomorphic, sedimentary, and stratigraphic information derived from a geomorphological survey. The mapping of landforms and the associated sedimentary packages provides a way to predict what locations may contain potential buried archaeological features. The geomorphic survey can help distinguish what landforms and accompanying deposits may have buried surfaces, soils, or be redeposited, as well as aid in determining whether the sequences are too old or young to contain archaeological materials.

Besides the adoption of technological innovations in GIS for mapping and chronometric studies, future applications may see further integration of the geomorphic survey as a key component of geoarchaeological and geoeological perspectives. As examples, the approaches to study human–environment interactions utilized by Colton (2009) in an archaeological and geomorphic survey in East Africa, and Schmitt et al. (2017) in the North American Great Plains rely heavily on geomorphological survey. In addition, in a partial response to attempts to understand the impact of humans on environmental systems, the geomorphological survey has the potential to play a valuable role in the study of the evolution of watersheds, with the goal of gaining a better understanding of the temporal and spatial parameters of human impacts and climate change on environmental systems.

A geomorphological survey is a key component of any archaeological or geoarchaeology field study. The main objective is to determine the landscape evolution of a region but it also includes specific studies of sediments and stratigraphic sequences. The geomorphic survey is primarily a field methodology but it also includes a pre-field planning and preparation stage and

can incorporate laboratory studies. The geomorphological survey takes a broad approach to understanding archaeological site context, examining the details of a site matrix, and placing this within the context of the landscape.

The geomorphological survey applies the study of landforms and landscape evolution using compositional, spatial, and temporal data integrating morphology, sedimentology, soils, stratigraphy, and chronology. This study of the landscape provides a broader-scale framework for correlations and sequencing (chronology) and more site-specific formation processes. When initiated before a regional archaeological survey (see FIELD SURVEY) is conducted, the geomorphic survey can produce a geomorphic model that can be used to predict the location and ages of archaeological or fossil sites as well as provide stratigraphic correlations. A geomorphological survey contributes to the objectives of understanding how the landscape has been influenced by natural and human systems, and the ways that Earth's physical processes have had an impact on the archaeological record.

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FURTHER READINGS

GPS (Global Positioning System)

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The use of satellite-based navigation systems such as the global positioning system (GPS) has been revolutionary within archaeological fieldwork and research. Unlike more traditional methods of survey, satellite-based systems have the capability of providing absolute positions without reference to known points and without the need to maintain lines of sight across a survey area. These technologies have enabled archaeologists to determine positions on the ground, to establish control for other survey methods, and to record three-dimensional (3D) positions rapidly and accurately for a variety of different purposes. From establishing control networks, to recording the location of trenches, finds, and features, to assisting in the automation of data collection, satellite navigation systems are improving the ways in which fieldwork can be conducted. Furthermore, they are enabling archaeological projects to become more ambitious. More recently, the integration of satellite-based navigation within portable devices such as smartphones has opened up a new range of opportunities for archaeologists.

While in many contexts the term “GPS” has become synonymous with satellite-based navigation and survey, it is one of a series of systems which are collectively referred to as global navigation satellite systems (GNSS). GPS was the first to start development in the early 1970s under the direction of the US Department of Defense, becoming operational in 1995. Initially, the system’s accuracy was purposely decimated through the addition of selective availability (SA), although this was discontinued in 2000. While GPS remains the most commonly used GNSS, the development of the Russian system GLONASS (GLObalnaya NAVigazionnaya Sputnikovaya Sistema, or GLObal Orbiting Navigation

Satellite System) also provides global coverage for positioning and surveying. The development of the GLONASS system commenced within what was the Soviet Union just three years after GPS with the constellation of satellites launched by 1995, although it was not until 2011 that the full orbital constellation was restored with global coverage. A system developed by the European Space Agency called Galileo was initiated in the late 1990s with full development since 2003 with the ultimate aim of global coverage. Similarly, the Chinese BeiDou Navigation Satellite System currently provides positioning across much of Asia and the Pacific but is aimed to provide global coverage by 2020. Other regional systems are also currently in development. The Indian Regional Navigation Satellite System (IRNSS), more commonly known as NAVIC (NAVigation with Indian Constellation), has been in development since 2010, with the final satellites launched in 2016 providing coverage for India with a buffer of 1,500 km.

Satellite-based navigation systems provide positioning using the principle of trilateration. Satellites each broadcast a microwave radio signal which can be received by appropriate equipment. Essentially, the distance between the satellite and the receiver can be calculated on the basis of the time delay between transmission and receipt of the signal. Satellites also provide an almanac of their predicted positions so that, since the positions of the satellites are known, the simultaneous measurement of distance from multiple satellites means that the position of the receiver can be determined. If four or more satellites are tracked by the receiver at any one time, 3D positions can be computed (see El-Rabbany 2006). Because of the way in which GNSS positioning works, best results occur when the survey equipment is able to receive signals from a well-spaced series of satellites, providing better geometry for trilateration. Where satellites are clustered, such as when the surveyor is working in a steep-sided valley with limited view of the sky, the satellite geometry can be poor, leading to a reduction in precision, often shown on surveying equipment as a dilution

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of precision (DOP). The result of poor geometry might result in either poor precision of position or the inability to record a specific point. Other factors also have an effect on the capabilities of satellite-based navigation. The sky view (enabling the receipt of satellite signals) can be affected by physical obstacles such as buildings and vegetation, and hence these systems will not normally work inside and work poorly in dense woodland. Sometimes errors can occur due to the reflection of signals off of nearby structures, and this is known as “multipath.” Additional errors might arise from the conversion between global, spherical coordinate systems (such as World Geodetic System 1984, or WGS84) and planar national grids.

Typically, the precision of points using GNSS will be limited to perhaps 5–10 m at best, although there are various ways of improving this, such as the assisted GPS (A-GPS) offered on some smartphones. Within this context, GNSS-receiving equipment is commonly referred to in relation to three grades which broadly equate with financial cost: navigational/recreational grade, mapping grade, and survey grade. Navigational/recreational grade receivers assume no additional correction, being that suitable positioning for way-finding is already provided at this lower precision. Mapping and survey grade systems are dependent on the receipt or collection of additional data to provide corrections. Traditionally, such accuracy was provided by the use of two receivers collecting the same data simultaneously, with one of the two remaining static throughout (normally on a tripod). Such “differential” approaches meant that relative precision could be calculated to the centimeter level, although absolute positioning still required correction to local detail. Absolute precision can be obtained by accessing commercial networks of static GNSS receivers, either directly through mobile phone connections or downloaded for post-processing to provide corrections. These services commonly work on a subscription basis and can provide differing levels of accuracy from less than 1 m to a matter of centimeters in real time.

The value of GNSS to archaeology extends across a wide range of different survey activities (see DIGITAL CARTOGRAPHY). Even at the navigational/recreational level, absolute positioning can assist in revisiting or locating sites

and finds much more rapidly and effectively than was previously possible, and has particular value in areas where local detail is lacking, such as moorland. The integration of such systems with mapping technologies such as geographic information systems (GIS) has brought much traditionally desk-based work into the field. Even with GNSS-enabled smart phones, the potential to take geo-referenced photographs which can be presented within freely available mapping software demonstrates some of the huge potential even at entry level. With the centimeter accuracy available through survey grade systems, much more has been possible. The ability to establish a network of absolute points across a site can facilitate much more efficient and effective survey using other methods. For example, the establishment of such control points has reduced the need for traversing using optical survey equipment, with the reduction in the potential for errors. As such, GNSS systems are frequently used to establish control for archaeological sites rather than for the collection of survey detail which is undertaken using other methods. However, satellite systems can also be used for on-site setting out and recording. From the establishment of site grids (e.g., for field-walking, geophysics, or excavation) to the recording of trench edges, grid pins, small finds, and levels, such systems can provide rapid collection of data by a single surveyor. Similar approaches are also possible using equipment such as robotic total stations (see TOTAL STATION), although without the capability of absolute positioning.

Given the speed of 3D data collection using satellite-based surveying equipment, such systems have opened up the capability for undertaking topographic surveys rapidly and effectively that can be processed to generate 3D surfaces. Such methods can be used to undertake rapid earthwork surveys, although there has been some debate about the value of such methods in relation to the subjectivity of traditional earthwork survey (e.g., Bowden and McOmish 2011). Despite these debates, the generation of surface models in software such as GIS provides the possibility of performing surface analyses and for the identification of ephemeral features that might not be recognized using traditional methods (e.g., Chapman and Van de Noort 2001). It also provides the capacity to integrate

topographies with other collected or modeled 3D data. Similar capability is now provided by technologies such as laser scanning (see LASER SCANNING) and photogrammetry (see DIGITAL PHOTOGRAMMETRY).

Perhaps one of the most exciting areas of development that has been facilitated through the use of satellite-based navigation systems lies in the way that receivers can be mounted with other sensors. In the case of geophysics, this has been revolutionary. Whereas traditional geophysical surveys normally required a grid to be established within which data were collected systematically, the ability to link GNSS positioning with geophysical data collection has meant that data can be collected directly without the need for any pre-established grid. Where the data are integrated and shown on screen to the surveyor in real time, surveys can be undertaken to avoid any gaps. Such systems have been effectively used in relation to pedestrian survey and also mounted on vehicles to undertake rapid data collection across entire landscapes (e.g., Gaffney et al. 2012).

The benefits of satellite-based surveying have opened up other avenues for archaeologists. Light detection and ranging (see AIRBORNE LASER SCANNING AND LIDAR) (LiDAR) surveys are positioned using GNSS, as are many drone systems (see DRONES), albeit with varying levels of spatial precision. Equally, the integration of satellite-based navigation within a range of mobile computers and other devices has meant that GIS can usefully be taken out into the field for the checking, modification, and collection of data. From its use on mobile devices through to the integration of GIS software within surveying equipment, GNSS has provided archaeologists with a range of new potential applications. From facilitating interpretation in the field to ensuring that the digital record from fieldwork is correct, mobile GIS is breaking down barriers between the field and the office.

Archaeology is a spatial discipline and so advances in the ability to measure and record positions are of key value. Depending on the system and equipment being used, satellite-based navigation systems provide a variety of different levels of precision in relation to absolute positions. The ways in which this capability has been used are varied, although perhaps the most

exciting developments lie in the integration between positioning and other applications, such as geophysics and mobile GIS. While this all provides archaeologists with many new and exciting opportunities, there are of course potential limitations. For example, the expense of some of the survey grade systems can reduce their availability for many users, although this concern should be tempered by the great benefits of the recreational grade systems and their broad accessibility on mobile devices such as smartphones, as well as by the continued use of other survey techniques. Ultimately, the increased sophistication of systems such as GPS has made positioning and surveying within archaeology much simpler and less labor-intensive, and this is already allowing archaeological projects to become more efficient and ambitious.

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Gradiometry

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Gradiometry is a type of magnetometry often used by archaeologists in which two magnetic sensors are attached to the same instrument (a gradiometer), usually one above the other. The spacing between the sensors varies, with 50 cm to 100 cm being common. During a typical gradiometer survey, the instrument uses simultaneous readings from each sensor to produce a single reading, the difference, at each data collection point. Like magnetometers, gradiometers are useful for detecting iron objects, burned earth (e.g., kilns, hearths, and house floors), and the accumulation of topsoil or archaeological midden in subsurface pits, trenches, and ditches.

There are at least two reasons why an instrument using two sensors (a gradiometer) is useful in archaeological contexts. The first and primary reason gradiometers are useful is for filtering out the daily fluctuations in the strength of the earth's magnetic field. The earth's magnetic field is all around us and it is constantly "turned on." Its intensity is recorded in units known as nanoteslas (nT), with stronger readings near the poles (over 60,000 nT) and weaker at the equator (below 30,000 nT). While the strength and positioning of the magnetic field generated by the earth is relatively stable, changing only slowly through time and across the planet (thus the utility of paleomagnetic dating), sources of magnetic disturbance from outside the earth, especially from solar flares, can create daily changes measuring hundreds of nanoteslas. Since these daily changes in magnetism are often as strong as or stronger than the magnetic signature of archaeological features, it is necessary to remove them when conducting archaeological surveys. Gradiometers filter out the daily magnetic field strength fluctuations by recording the difference between

the readings measured by each sensor. As the instrument is moved along the surface at a fixed height, and assuming the sensors are stacked one above the other, in principle the bottom sensor detects the earth's magnetic field plus any changes to it caused by archaeological features at or near the surface, while the top sensor detects just the earth's magnetic field. Subtracting the top sensor's reading from that of the bottom leaves the effects caused by things buried in the ground. Since daily fluctuations in the magnetic field are detected by both sensors equally, they are filtered out. A second reason gradiometers are useful in archaeology is they allow the surveyor to collect useful data closer to large iron objects, such as buildings, vehicles, and iron fences.

Gradiometers have been in use on archaeology sites for well over 50 years. Initially they were referred to as differential magnetometers (Aitken 1961), and the sensors were of the proton precession type. Today, archaeologists more often use gradiometers with fluxgate or cesium vapor sensors. The sensors in most fluxgate gradiometers are set at a fixed distance, ranging from 50 cm to 100 cm, while the sensors of cesium vapor systems are adjustable. Most gradiometers in use today can detect magnetic field differences of as little as 0.1 nT. A typical archaeological survey with a gradiometer may record eight to ten readings per meter along transects spaced 25 cm to 50 cm apart (for example, see Figure 1). Single and dual gradiometer systems are often carried; larger cart-based systems with three, four, five, ten, or more gradiometers are pushed or towed. Such towed systems can be used to cover vast areas, from 2 to 20 ha in a single day.

SEE ALSO: Airborne Remote Sensing; Electrical Resistivity; Electromagnetic Conductivity; Ground-Penetrating Radar; Magnetic Field Gradient; Magnetic Susceptibility; Magnetometry; Radar; Visualization of Magnetometer Data

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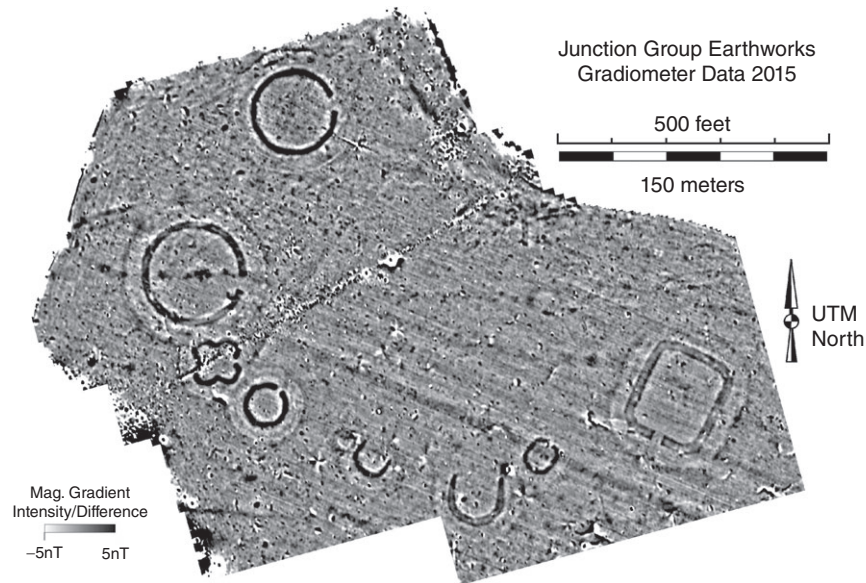


Figure 1 Gradiometry survey results, 2000-year-old earthwork site, Ohio.
Source: Google.

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Ground-Penetrating Radar

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Ground-penetrating radar (GPR) is a shallow geophysical technique that produces many different three-dimensional datasets of the buried materials. Buried units can be analyzed by interpreting many two-dimensional reflection profiles that are closely spaced within grids and larger scale map-view images. The method can be used to produce images of buried archaeological features and associated soils and sedimentary units within about 4–5 m of the ground surface, but sometimes deeper if ground conditions allow deeper radar energy penetration. It can be used as an exploration tool for finding buried archaeological sites, for projecting information from standard excavations into adjacent areas (Conyers 2013), and as a method for testing hypotheses about human behavior (Conyers 2010; Conyers and Leckebusch 2010) that relate to the placement of features on a buried landscape, or the shape, orientation, and placement of buried remains (Conyers 2009). It is particularly useful in geologically complex areas, where there are associated sedimentary layers and soil units associated with archaeological materials (Conyers 2016). When archaeological features can be discriminated and placed within a geological context, complex burial conditions and human remains within them can potentially be understood in three-dimensions.

The GPR method consists of measuring the elapsed time between when waves of electromagnetic (radar) energy are generated at a surface antenna, transmitted to depth, reflected from buried discontinuities, and then received and recorded at the surface. Reflection data are most often collected by moving antennas along the ground surface in transects, while energy is transmitted, reflected, and recorded in closely

spaced traces, with each trace being a record of reflected waves at one location. Traces are usually spaced between 3–5 cm along linear transects and reflections recorded within a pre-programmed time window (within two-way travel time, measured in nanoseconds). The distribution and orientation of reflections generated from layers and features of geological or archaeological importance are then identified and images are produced in two-dimensional profiles consisting of many hundreds of traces stacked vertically (Figure 1). When many profiles consisting of thousands, or hundreds of thousands, of reflections are resampled and oriented in three-dimensional space, images of reflections can be produced in amplitude slice-maps of any orientation (Figure 2) or three-dimensional visualizations of the stronger reflections called isosurfaces (Conyers 2013).

Production of radar reflections

When radar waves are transmitted from a surface antenna through various materials in the ground, their velocity changes, depending on the physical and chemical properties of the ground. Significant velocity changes often occur at interfaces between materials of different composition, water saturation, or mineralogy. When propagating radar energy abruptly changes velocity at interfaces, some is reflected back toward the surface, which is detected and recorded at a receiving surface antenna. The amplitude of recorded waves is proportional to the changes in velocity. When radar wave velocity is calculated, travel times can be converted to depth, and a three-dimensional dataset is produced. In this dataset, the amplitudes measure the relative differences in material type in the ground, and the travel time measures their depth below the surface.

Point source reflections often occur in the shape of hyperbolas (Figure 3). This shape is produced because most GPR antennas produce a transmitted radar beam that propagates downward from the surface in a conical pattern,

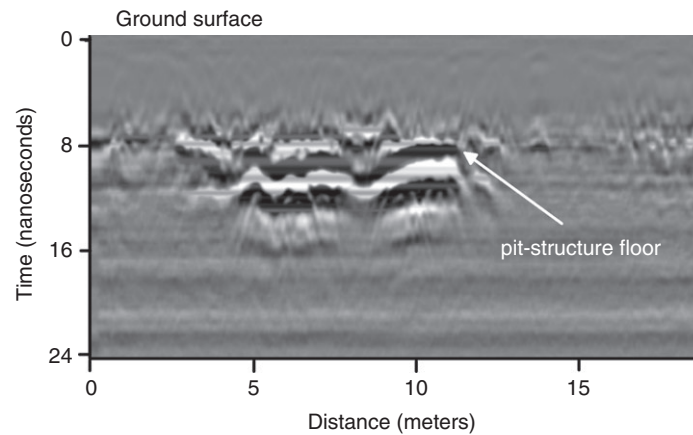


Figure 1 Two-dimensional reflection profile showing a buried pit house floor.

radiating outward as energy travels to depth. Radar waves will therefore be reflected from buried point sources that are not located directly below the transmitting antenna but are still within the propagating beam of moving waves. Oblique radar waves travel paths to and from the ground surface to point sources in the front and back of the antenna are longer (as measured in radar travel time) but the reflections generated are recorded as if they were directly below, but just deeper in the ground. As the surface antenna moves closer to a buried point source, the receiving antenna will continue to record reflections from the buried point source prior to arriving directly on top of it and continue to record reflections from it moving away. A reflection hyperbola is then generated with only the apex of the reflection denoting the actual location of the object in the ground, with the arms of the hyperbola creating a record of reflections that traveled the oblique wave paths. In some cases, only half of a hyperbola may be recorded, if just the corner or edge of a more planar feature is causing a discrete reflection, such as the edge of a buried house floor or platform. The shape of hyperbolas can also be used to calculate radar travel velocity in the ground (Conyers 2013). Hyperbola analysis is therefore an extremely efficient and accurate way to convert all radar travel times to depth in the ground.

Variables affecting GPR

The success of GPR surveys depends on soil and sediment mineralogy, clay content, ground moisture, depth of burial, surface topography, and vegetation. Radar wave penetration, and the ability to transmit energy through the ground and reflect it back to the surface, are often enhanced in a dry environment, but dry conditions are not necessarily a prerequisite, as surveys in wet environments can be successful as long as the media in the ground are not electrically conductive. The mineralogy of materials in the ground is also important, especially clay type and content. Sediments that contain electrically resistive clay minerals, such as kaolinite, are excellent at allowing the transmission of radar waves, while bentonite, montmorillonite, and other electrically conductive clays are generally poor for transmission, as radar energy is conducted away and propagation of waves ceases. Fresh water is an excellent medium for radar energy transmission, and the propagating waves can travel to great depths in lakes and especially through glacial ice. However, when fresh water comes in contact with electrically conductive materials, attenuation of the propagating energy occurs. Salty or brackish water will not allow radar energy transmission to any depth.

The depth to which radar energy can penetrate and the amount of definition that can be expected from reflections generated at buried surfaces is partially controlled by the frequency of radar

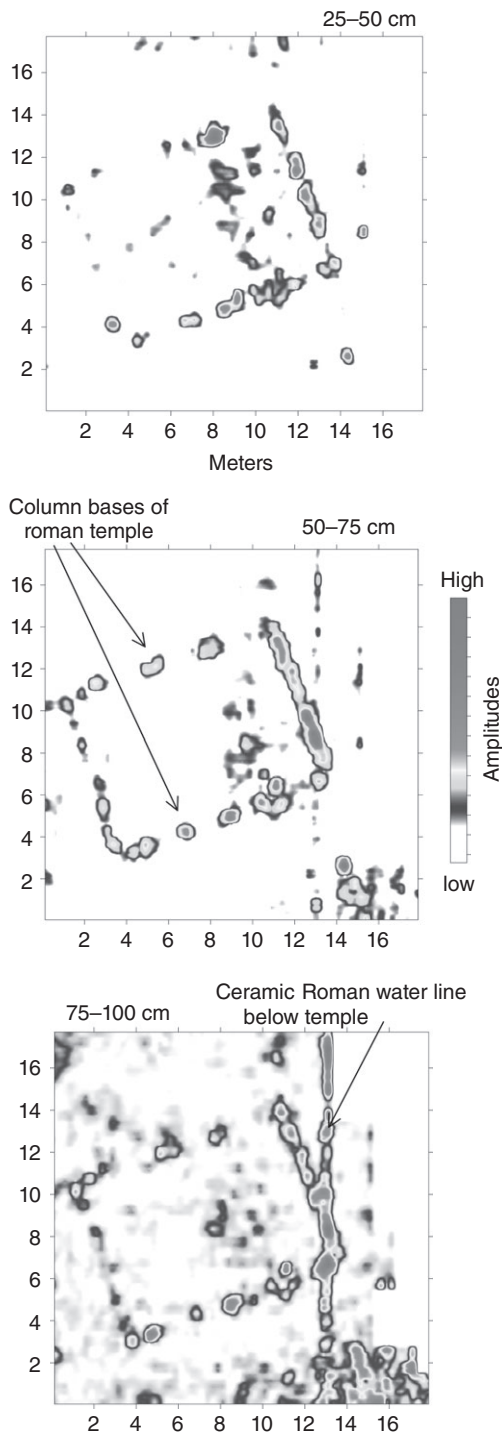


Figure 2 Horizontal amplitude slice maps showing a buried Roman temple.

energy transmitted, which is a function of the antenna used. Standard GPR antennas propagate radar energy ranging in band width from about 10 to 1200 megahertz (MHz). In general, lower-frequency waves propagate deeper into the ground, but have less subsurface resolution. For instance, 200 MHz antennas can potentially transmit energy to 4 or 5 m depth, but reflections are generated only from large features, in the order of a meter or so in dimension. A higher-frequency 900 MHz antenna can potentially resolve features in the order of 10–20 cm in maximum dimension, but is capable of energy transmission to about a meter or less in the ground. In electrically conductive ground all radar energy, no matter what frequency, will attenuate at a very shallow depth.

Radar energy becomes both dispersed and attenuated as waves move into the ground from surface antennas. Energy that is reflected back toward the surface will suffer additional attenuation by the material through which they pass, before finally being recorded at the surface antenna. Therefore to be detected as reflections, important subsurface interfaces must not only have sufficient electrical contrast at their boundary but also must be located at a shallow enough depth where sufficient radar energy is still available for reflection. As radar energy is propagated to increasing depths, the signal becomes weaker as it spreads out over more surface area and is absorbed by the ground, making less available for reflection. For every site the maximum depth of resolution will vary with the geologic conditions and the equipment being used.

GPR images

Radar reflection profiles are the most basic form of data presentation, which show distance along transects on the horizontal scale and depth in the ground where reflections of varying amplitude were recorded on the vertical axis (see Figure 1). Depth is recorded in two-way travel time, but can be converted to depth, if the propagating wave velocity is calculated. If the ground is stratigraphically simple, and buried archaeological features are distinct, they can be readily viewed, mapped, and interpreted

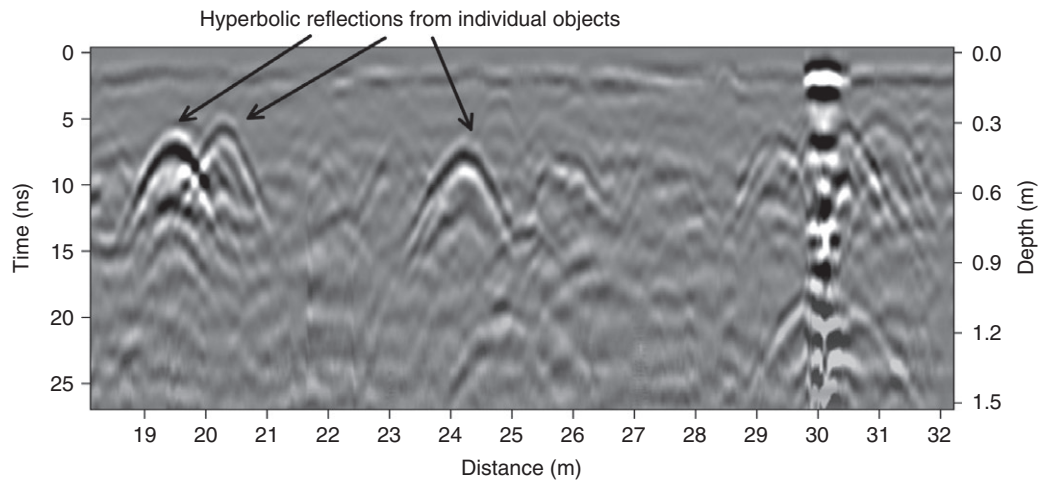


Figure 3 Hyperbolic reflections displayed in profile, generated from individual objects in the ground.

in profile form. However, when many tens or hundreds of profiles are collected in grids, individual profile interpretation can be laborious, and the three-dimensional aspects of reflections are difficult to image and understand and differentiate from other geological units. To overcome this complexity of an overwhelming amount of data in three-dimensional space, slice-maps that produce images of relative amplitudes of reflected waves throughout a grid of reflection profiles can be produced (see Figure 2). These types of maps are generated by sampling, gridding, and averaging all waves in all reflection profiles in a grid and displaying various amplitudes in defined slices of any thickness or orientation. Different amplitudes are then colored, corresponding to the location of buried materials of interest. In geologically complex areas, stratigraphic layers will generate high-amplitude reflections as well as those of archaeological features and can be misinterpreted unless there is an understanding of the nature of all strata (Conyers 2016). Simpler ground conditions, however, will allow the reflection amplitudes of buried archaeological features to be readily imaged in both profiles and amplitude maps.

There has always been a bias in GPR toward analyzing and mapping only the higher-amplitude reflections, but areas of low or no amplitude can also be important. If buried archaeological features of interest do not reflect radar waves, such as uniform earthen architecture, they can still be

imaged and interpreted as zones in profiles and maps with no, or only low, amplitudes (Conyers 2013). Only an understanding of the reflectivity of the various materials in the ground will allow accurate interpretation of GPR images.

Complexities in GPR interpretation

If the geological materials in the ground are complexly bedded, the computer sampling methods for amplitude mapping will display reflection amplitudes from one continuous horizon as if it was a series of aurally restricted “anomalies” at various depths within each slice. As the layers in the ground are dipping, most GPR processing software used to generate three-dimensional images will generate extraordinarily busy “anomaly” maps that are mostly irrelevant to the final interpretation as slices cross horizons at various depths. The amplitude maps are then imaging only bedding horizons that may be located in any one slice. Any archaeological features within this package of bedded material will be effectively hidden within the final images. In this case only an understanding of the basic reflection information from which the images are produced within a geological context (Conyers 2016) will allow an accurate final product.

Another basic question with GPR interpretation (Conyers 2012) is what may be producing the reflections in a dataset. Often this can only

be determined from viewing reflections in profiles and understanding what produces radar reflections and then correlating those directly to excavations or other information about the ground. These basic interpretations make sense as interfaces between archaeological materials and surrounding sediments and soils that produce the high amplitude reflections can be understood. For instance, in an area with buried homogeneous clay walls and floors, only the horizontal floors are visible in GPR profiles with the walls being nonreflective as they are composed of clay and other fine-grained materials with no interior bedding planes or other interfaces from which to reflect energy. Any vertical interfaces between the walls and surrounding materials are also not reflective, as radar waves transmitted from the surface move parallel to these vertical boundaries, or if radar waves intersect the interfaces they are reflected away from the surface recording antenna and not recorded. When viewed in reflection profiles the vertical clay walls appear as areas of no reflection and unless an interpreter understands the nature of the materials in the ground these features will often go unnoticed.

Using GPR for archaeological interpretation

Archaeological geophysics is often used as a method for discovering buried archaeological remains and less often as a dataset for interpreting aspects of human history and anthropological hypotheses relating to culture. However, GPR with its three-dimensional mapping ability, can be used to test ideas about humans in ways that are similar to standard archaeological methods (Conyers 2010; Conyers and Leckebusch 2010). If architecture, site organization, or any aspects of human modification and archaeological remains on the landscape GPR can be an excellent tool (Conyers 2009). The GPR method can be an especially powerful tool when combined with standard archaeological excavations, especially when the geophysical images can be used as a guide to the placement of subsurface tests that test ideas of interest.

Ground-penetrating radar has the unique ability of near-surface geophysical methods to produce three-dimensional maps and images of buried architecture and other associated cultural and natural features. It can be performed in any type of ground, as long as the sediments and soils are not highly electrically conductive. Using high-definition two-dimensional reflection profiles, three-dimensional maps of amplitude changes can define physical and chemical changes in the ground that are related to archaeological and geological materials of importance. Interpretations that use individual two-dimensional reflection profiles combined with images of grids of many tens or hundreds of profiles can be used to help understand buried archaeological sites, especially those that are geologically complex. When these data and maps are used to test ideas about human adaptation to ancient landscapes, they offer a powerful and time-efficient way to study ancient human behavior, social organization, and other important archaeological and historical concepts.

SEE ALSO: Electrical Resistivity;
Electromagnetic Conductivity; Gradiometry;
Magnetic Susceptibility; Magnetometry

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IR Thermography

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Introduction

IR thermography (IRT) is a non-destructive inspection technique that measures the electromagnetic energy emitted from a surface in the infrared (IR) radiation band, which is normally referred to as thermal radiation. By measuring the emissivity of the surface, which depends mainly on its color and on the reflectivity of the surrounding environment, it converts the thermal radiation to temperature, and therefore is able to display temperature distribution, which is represented as an image in false colors. Information is obtained by building on the fact that the radiation effect is closely correlated to the temperature of the radiating object. This is possible since thermography provides temperature monitoring of different sample surface areas, allowing a time-resolved analysis of the heat diffusion process in the sample including its subsurface structure. As regards these measurements, disturbance effects are offered by air temperature, solar radiation, and plant physiological parameters.

Applications of IRT are widespread in various fields from science, civil and military industries to medical diagnostics, fire rescue and maintenance, and so on, in some cases offering indications, normally over a very short timeframe, of the effect of the application of a stress (mechanical or thermal). The duration of the thermal stress introduced can in some cases be very short, so that it can be described as a pulse ("pulse thermography"). Lockin thermography, where the infrared wave signal is produced in response to an excitation, normally created by eddy current or ultrasound techniques, has recently generated interest for archaeological surveys.

Thermal radiation can simply be produced as the effect of illumination of the surface, in some cases barely, by solar light. The hidden assumption in this case is that the differences in thermal radiation are offered by structural differences in the surface properties or even at some depth below the surface, so that considerations can be made on the presence of different structures, which are not visible to the naked eye. In particular, the passive use of IRT is quite widespread in the inspection of a number of artifacts, including engineered structures and surfaces. The application of this technique is based on the assumption that parts with different properties emit different amounts of energy. In the case of historical buildings, it is possible to detect cracks, de-adhesion, for example of plaster from the wall, alteration of material consistency, and so on. In particular, by selecting the most adequate thermographic technique, it is possible to monitor the conservation state of artworks in time, and detect the presence of defects in different types of materials, such as concrete, masonry structures, or bronze.

In general terms, IR thermography is able to reveal features with sufficient contrast in thermal inertia within the complex of materials of which they are composed. Thermal inertia can be defined as the product of thermal conductivity and volumetric heat capacity of a material. To improve the quality of the image, these are repeatedly acquired during periods of the diurnal cycle where such contrast is the highest.

Archaeological thermography

IR thermography can be used as a remote sensing tool to identify, evaluate, document, and assess cultural resources. Analyzing surface temperature rates of change and their spatial variations allows not only evaluation of the incidence of thermal decay on the whole phenomenon of stone decay, but also other factors affecting the state of conservation of architectural and archaeological

heritage such as moisture, salts, or mechanical disruption. This is effective for brick, stone, and mortar, but less so for wood with its lower heat capacity.

Aerial thermography, normally making use of IR wavelengths between 8–14 microns and acquired together with panchromatic photographs (at shorter wavelengths), originally applied to the presence of ancient cropping areas for its ability to reveal surface and subsurface cultural features, has also been proved as a survey method for archaeological sites. Another possibility that has been more recently explored is the use of kite-driven aerial thermography to reveal many subsurface remains, such as at a mound center in Mississippi (Haley, Johnson, and Stallings 2002). Here, thermal imagery was able to document subsurface house remains, in particular revealing ellipses of daub, a brick-like material produced when houses were burnt to make space for new constructions. The diurnal variation in their thermal values was acquired, by recording sunrise and sunset times. Several recent studies have explored the archaeological potential of much higher resolution thermal images. For example, Ben-Dor et al. (2001) collected imagery from a helicopter to detect subsurface stone architecture from an altitude of 1,333 metres over the Golan Heights in Israel, while Buck, Sabol, and Gillespie (2003) used thermal images collected by a camera mounted on a platform to reveal differing concentrations of surface artifacts, such as obsidian pottery.

Limitations to archaeological thermography occur in the presence of vegetation, which may confuse the image, so that vegetation temperature is better monitored separately. Thermography can detect features at or near the ground surface, such as pits, ditches, and field boundaries, as well as buried architectural features up to half a meter below ground (Bellerby, Noel, and Branigan 1990). More recently, the availability of multispectral methods of airborne remote sensing allows the measurement of vegetation indices, including crop variation (Challis, Kincey, and Howard 2009).

Further possibilities are offered by the combined use of IRT with ground-penetrating radar (GPR), employed together for the in-situ inspection of Pompeii and Nora (Carlomagno et al.

2011). IRT is also capable of elucidating the state of bonding between plaster and its support in Roman masonry, offering a clear view of the construction details concealed under the finishing layer, such as the shape and layout of the masonry units (Colla et al. 2008). In the case of marble structures, especially when trying to measure the surface roughness, which may be useful to elucidate the history of the artifact, promising characteristics were also indicated by the combined use of 3D profilometry with pulsed thermography (Avdelidis et al. 2004).

At a larger scale of inspection, two seasons of aerial surveys at Double Ditch archaeological site offered complete coverage by digital color video, high-resolution color stills, and thermal imaging in the 10 microns band, acquiring data from a low- and slow-flying powered parachute platform, 250–500 m above the ground. IRT was used as an essential part of complete geophysical surveys, which included magnetic gradiometry and electrical resistivity methods, and large areas of ground-penetrating radar (GPR) and electromagnetic induction surveys (Kvamme, Ernenwein, and Markussen 2006). The application of IRT in combination with other techniques, such as high-frequency electromagnetic techniques (GPR) for the survey of archaeological sites, allow surveys on land at a shorter distance and with higher resolution. IRT could be used in the first instance to supply a 2D map, which would include detailed information about surface and shallow anomalies. Then GPR could offer a broader 3D description of the horizontal and depth position of features and defects, allowing the survey to descend to greater depths. However, this appears to be very challenging, requiring a microlight aircraft with an experienced pilot, ideal weather conditions, and very time-consuming image processing work to rectify and mosaic the images into a usable map.

For this reason, most recently the use of unmanned aerial vehicles (UAVs) has also been proposed, with methods such as airborne thermal prospecting based on the difference between the thermal characteristics of buried remains and the environment in which they are buried, and integrating thermal cameras into the UAV structure, with further processing through photogrammetry software (Poirier, Hautefeuille, and Calastrenc

2013). Aerial surveys at the Chaco-period Blue J community in northwestern New Mexico enabled easy mapping of the size and organization of most habitation sites, while also revealing previously undocumented architectural features (Casana et al. 2014).

Future perspectives

Interest in IRT for archaeological inspection at different scales, from that of walls and artifacts to the wider assessment of a whole archaeological site, is rapidly growing. This is due to both the decrease in cost of the available thermal cameras, as well as rapid improvements with regard to spatial resolution (reaching levels of 1024×768 for most recent models), while substantially fine-tuning thermal resolution almost to the level of K/100. At the same time, advances in photogrammetric image processing software packages allow easier composition of images into a coherent picture of the archaeological site. This is coupled with the combined use of different techniques, including ground-penetrating radar, while improvements in aerial thermography have come from the development of more reliable unmanned aerial vehicles.

SEE ALSO: Archaeological Videography

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Magnetic Field Gradient

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Study of the magnetic field gradient for archaeological prospecting involves measurements of the Earth's magnetic field on a regular or irregular grid of observation points at the investigated site (Aitken 1958). Survey of magnetic gradient is a nondestructive method employing measurement of the total magnetic field. It allows effective implementation of prospection during archaeological planning for excavations (Eppelbaum, Itkis, and Petrov 2000) and facilitates rapid outlining of the archaeological potentialities in the investigated zone. Such investigations are most commonly coupled with additional information on geology and (archaeo-) morphology to better characterize the areas with high archaeological potential. In special cases, these are used as an alternative to excavations to avoid site destruction (Eppelbaum et al. 2000).

Most modern instruments have evolved from either the fluxgate or optically pumped technology. These modern instruments have impressive speed in the field, due to automatic data recording and use of mechanically efficient methods of towing (Becker 1999). Recent studies have showcased detailed maps conspicuously depicting buried archaeological features such as ancient cities, and pre- and protohistoric anthropogenic elements, such as pits and ditches (Aubry et al. 2001).

Methodology

Prior to starting the archaeomagnetic survey, it is critical to investigate the quaternary geological landforms (lithology, topography) covering the archaeological sites (Aubry et al. 2001). This investigation delineates the natural background signal. Natural processes and anthropogenic

activities may enhance or lessen the magnetic signals. These processes include pedogenesis (which may cause intense transformations of soil), agriculture, forestry, deforestation due to natural or anthropogenic fire, and transportation of sediments and rocks down the slope. In summary, a careful estimation of the site is critical for an effective detection and interpretation of the archaeological feature.

A conspicuous detection further depends on the mesh size, investigation depth, and archaeological nature of the feature, such as kilns (distinct magnetic field gradient) and caves (weak magnetic field gradient). For archaeomagnetic prospecting, spatial resolution, sensitivity, and speed are highly desired (Becker 1999). Spatial resolution is determined by the step size in the sampling mesh. Generally, the step size is between 5 and 20 m. Such mesh allows a rapid and effective survey. Notably, the probability of detection of a feature is more if its diameter is at least twice the size of the step in the sampling mesh. In recent times, there has been a shift away from pre-gridded surveys towards real-time global positioning system (GPS) navigation. This allows greater integration and visualization of disparate data, along with precise data location that increases the quality and reduces processing (Gaffney 2008).

The backbone of high-sensitivity magnetic prospecting is the reduction of the natural and technical temporal geomagnetic variations caused by micropulsations, power lines, and so on. This may be achieved by measuring the difference between two sensors in vertical gradiometer or variometer mode (Becker 1999). Thereafter, the readings are corrected for changes in the ambient field, caused by diurnal variations and magnetic storms.

An archaeological geophysicist has a variety of magnetometers and instrumental setups to choose from: vertical or total field, a single sensor, gradiometer or differential mode, handheld or nonmagnetic cart, human- or vehicle-powered. The most frequently employed magnetometers are: (1) proton instruments,

(2) vapor magnetometers, (3) fluxgate gradiometers, and (4) superconducting quantum interference device (SQUID).

Proton instruments were the earliest magnetometers used for surveying magnetic field gradient for archaeological purposes. They made magnetic prospecting practicable in archaeology. They have inherent advantages, such as absolute reading without calibration and directional sensitivity, and no requirement for a setting-up procedure due to high-precision construction. Nevertheless, due to their polarization-measurement mode of operation, they are much slower than the latest instruments and are less adapted for rapid archaeological surveys that demand speedy gathering of high-density information (Clark 2003).

The alkali vapor magnetometer (cesium or rubidium) is a highly sensitive instrument. The University of Pennsylvania Museum of Archaeology and Anthropology initiated its archaeological use. These magnetometers have the advantage of producing an effectively continuous signal and can be used in the differential form, but they are expensive and prone to breaking down because of their complexity (Clark 2003). For normal archaeological prospecting, their high resolution (~ 0.01 nT) rarely has a practical advantage over fluxgate and proton instruments with 0.1 nT resolution.

The fluxgate gradiometer is the most used instrument for archaeomagnetic prospecting. Two sensors are mounted, with their axes vertical, on a vertical pole separated by a distance of 1.2 m. The outputs of the two sensors are subtracted from each other to obtain the resultant. The resultant is governed by the vector addition of the two contributions, such that $(B_{\text{Earth}} + B_{\text{Anomaly}}) - B_{\text{Earth}} \approx B_{\text{Anomaly}} \times e_{\text{Earth}}$, where e_{Earth} is the unit vector in the direction of the Earth's magnetic field (Blakely 1996). In cases where the Earth's magnetic field is undisturbed, the resultant is zero; however, when it is disturbed by a buried archaeological feature the resultant is nonzero. For interpretation, the resultant is amplified and fed to a phase-sensitive detector. The gradiometer suffers from a slight disadvantage due to the cyclic mode of operation, where each individual reading is separated by a pause of a few seconds.

SQUID measures true gradients of the magnetic field with high sensitivity, in the order of 10^{-15} nT. Its inherent advantage of high sensitivity is complemented by the incredible data acquisition rate that allows traversing at high speeds of 30 km/h. Although SQUID outperforms other magnetometers, it has two major limitations. It must be kept very cold for effective superconductivity, and it has a short baseline, which is essential to suppress the Earth's field and the field from other nearby mechanical devices. Nevertheless, SQUID field systems are being used for archaeomagnetic prospecting (Linzen et al. 2007).

Advantages of archaeomagnetic prospecting over traditional techniques

Archaeomagnetic prospecting is rapid and inexpensive. Thus, it is often used to survey and rescue probable archaeological sites in areas that are currently under intense pressure from urban development (Aubry et al. 2001; Bates, Bates, and Whittaker 2007). Inexpensive archaeomagnetic prospecting is preferred over traditional expensive survey through boreholes or trenches. This is particularly the case where the overlying deposits are more than 5 m thick and are composed of hard sand and clay, or gravels (Bates et al. 2007). Besides the financial consideration, archaeomagnetic prospecting surpasses traditional borehole survey because the data are collected rapidly, with high density, and are largely free from periodic errors (Gaffney 2008). Archaeomagnetic prospecting does not disturb the soil or cause damage. In contrast, after archaeological excavation, sites are prone to weathering and vandalism. Furthermore, excavation itself implies destruction. Among all geophysical techniques, archaeomagnetic prospecting is most suitable for identifying pits, wells, ditches, and any other types of backfilled features in the open field; and it is exclusively applied for kilns, slag deposits, and other features related to intensive use of fire (Aubry et al. 2001).

Shortcomings of archaeomagnetic prospecting

Archaeomagnetic prospecting, by studying magnetic field gradient, is less suitable than the resistivity method for identifying stone and brick buildings, roads and urban networks, and surrounding walls. Similarly, electromagnetic methods are preferred for detection of metal objects. Hollow spaces, such as caves and tombs, are generally difficult to investigate, especially when their height exceeds the other two dimensions. Such features demand a combination of several geophysical techniques.

Estimation of the depth of features is essential, as it helps to evaluate the potential difficulties and cost of a scheduled excavation. However, determination of the depth, from magnetic field gradient, is tricky. Moreover, numerous natural and artificial noises interfere with the magnetic signals. The most harmful factor is the oblique magnetization in some parts of the world. For example, the inclination of the Earth's magnetization vector in Israel is about 45° . Other factors include complex geological structures and the influence of modern iron-containing objects (Eppelbaum et al. 2000).

In summary, magnetic field gradient provides a robust, rapid, and economic procedure for archaeological prospecting. Depending upon the objectives, it may yield a preliminary perspective of the buried feature or a detailed view, which may be used as an alternative to excavations to avoid site destruction.

Olmec monumental elements: case study

We studied the magnetic field gradient in the San Lorenzo Tenochtitlán, a lowland area of southern Veracruz, Mexico ($17^\circ 45' 24''$ N and $94^\circ 45' 42''$ W). The objective was to explore specific selected areas for structures, monuments, and archaeological pieces of Olmec art such as colossal heads, thrones, massive altars, and animal figures. (Figure 1). The Olmec were perhaps one of the oldest and greatest societies in Mesoamerica. The archaeological pieces are commonly carved from volcanic rocks, such as basalt, that probably came from rock outcrops,

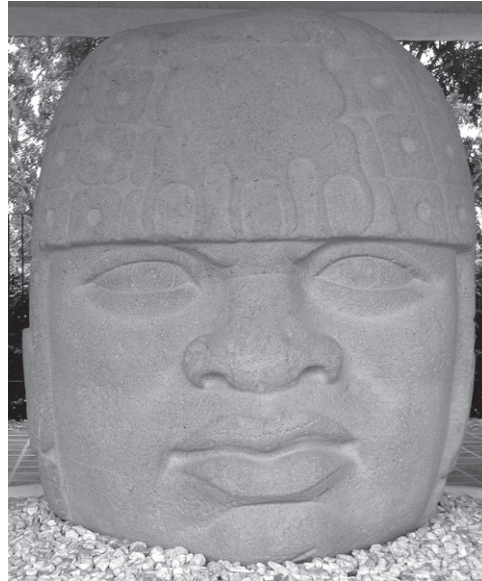


Figure 1 Olmec colossal head (weighs between 6 and 50 tons), sculpted in ca. 1500–400 BCE. Source: Picture provided by Ann Cyphers.

approximately 60 km northwest of San Lorenzo. The contrast in the rock magnetic properties between the volcanic rocks and the enveloping soil cover makes this method most suitable.

We used the Gradiometer G-856 for the magnetic fieldwork, measuring with a 1-m step size along 100-m-long lines. A gradiometer setup (sensors separated by 0.79 m) was used to acquire two measurements at each step (one from each sensor). The data acquired were edited, corrected for inaccuracies during acquisition, and processed in the Magloc program supplied by EG&G Geometrics. Magloc provides a summary data grid, as the amplitude of the magnetic anomalies (Figure 2) (Oropeza-Villalobos 1999).

In cases where an area of interest is identified in the magnetic anomaly map, we used the separated anomaly to make a quantitative evaluation (magnetic modeling, using Oasis Montaj-GMSYS software) to identify the location, depth, shape, and size of the magnetic bodies (for detailed methodology see Grant and West 1965). This allowed us to locate unfinished colossal heads weighing around 20 tons. This discovery was archaeologically relevant to expand the basic knowledge of the Olmec society that prospered during the Preclassic period.

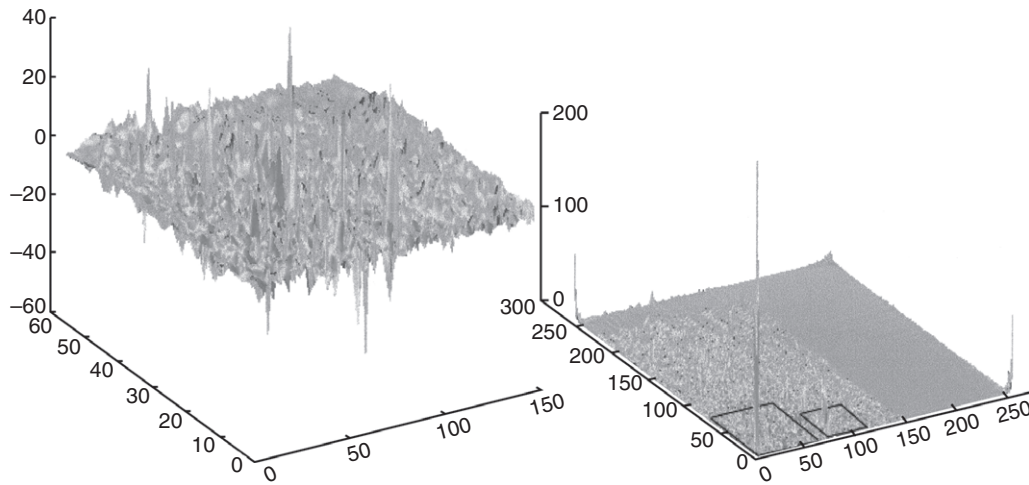


Figure 2 Three-dimensional representation of data from the magnetometer (left). Anomaly magnetic map generated after applying the second derivative (right). Areas of interest are marked with two black rectangles.

SEE ALSO: Magnetic Susceptibility

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Magnetic Susceptibility

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Magnetic susceptibility (K) is a dimensionless quantity that indicates the degree of magnetization in a material in response to an applied magnetic field. It is important to note that for most of the rock magnetic measurements applicable in archaeology, K is measured at the low applied magnetic field. K of a material depends, most importantly, on the mineralogy. Ferromagnetic minerals, such as magnetite, have high K ($> 10^{-3}$ SI units), while paramagnetic minerals, such as chlorite, have K in the order of 10^{-6} SI units. Diamagnetic minerals, such as quartzite, and most organic materials have $K < 0$ SI units. Thus, measurement of K in natural conditions may provide basic information on the mineralogy, whereas measurement and comparison of K in different ambient conditions reveals precise information on the magnetic mineralogy. This information, when coupled with additional archaeological, geological, and geographical information, provides important details about ancient societies.

Measurement of bulk magnetic susceptibility

The most common methods used reveal K under various ambient conditions. Such methods are very reliable, as they provide clues to magnetic mineralogy and domain size. These methods are as follows.

K of soils and archaeological artifacts may be measured in situ (without physically disturbing) or with samples in the laboratory. There are numerous handheld portable susceptibility

meters available such as SM-30 (Heritage Geophysics) and MS3 (Bartington Instruments). They provide rapid measurements at a unique frequency at room temperature. For more precise measurements, using laboratory-based instruments, there is the MFK-1 (AGICO). It facilitates measurement of K under various ambient conditions, such as high or low temperature, and an applied magnetic or electric field of a constant or varying frequency and strength.

Thermomagnetic curves are plotted by measuring K at various temperatures, usually from -192 to 700°C . K of each mineral has a characteristic relationship with temperature, which depends on the mineral's magnetic grain size and chemical composition. A slight variation in either changes the characteristic shape of the thermomagnetic curve. These curves therefore provide quantitative magnetic mineralogy, such as the content of Ti in magnetite or in maghemite, and qualitative information on the magnetic domain size (e.g., Agarwal, Kontny, and Greiling 2015; Agarwal et al. 2016; Alva-Valdivia et al. 2017).

Hysteresis curves are plotted by measuring the magnetic moment in a variable applied magnetic field. The shape of a hysteresis curve provides quantitative information about the magnetic grain. Modern instruments have the capability of combining the thermomagnetic and hysteresis curves, by enabling measurement of the magnetic moment in varying fields and at various temperatures.

Gathering additional information

Complete and effective archaeological interpretation demands careful study of the geological character of the area, such as paleogeography. For example, in the case of paleosols it is critical to understand the natural pedogenesis in the area. Similarly, in the case of archaeological artifacts made of various rocks and ores it is important to understand the geological setting of the nearby rock formations.

As discussed earlier, K depends on several factors. Arguably, the most important is the mineralogy. Therefore, rock magnetic methods are usually coupled with additional chemical investigations for effective interpretation. The most common methods for determining mineralogy and chemical composition are X-ray fluorescence (XRF), wavelength dispersive spectroscopy (WDS), energy dispersive X-ray (EDX), inductively coupled plasma mass spectroscopy (ICP-MS), and atomic absorption spectroscopy (AAS).

Case study 1: Identification of anthropogenic activity in La Playa, Sonora, Mexico

The archaeological site of La Playa, Sonora, shows conspicuous evidence of human occupation since the Late Pleistocene. However, the society reached its peak in the Late Holocene, ca. 3,500 years ago (Carpenter et al. 2015). The site is spread over an area of about 10 km², over an alluvial fan formed in the foothills of the Sierra Boquillas (Carpenter et al. 2015).

Two pedosedimentary profiles are described in the area: the 14,570 ± 340-year-old San Rafael Paleosol (SRP) and 3,985 ± 105-year-old Boquillas Paleosol (BOP) (Cruz-y-Cruz et al. 2014). Samples were collected for identification, description, and classification of soil horizons. Free iron (Fe_d) was separated (for technique see Mehra and Jackson 1960), and AAS was performed using the Perkin Elmer Model 3110 in the Department of Soil Science, Institute of Geology, UNAM. For measuring K , samples were collected every 10 cm in the entire profile and dried at room temperature and placed in plastic cubes of 8 cm³. K at low and high frequency (LF and HF) was measured with a Bartington MS2 susceptibility meter in the Institute of Geophysics, UNAM.

In SRP, K displays conspicuous maxima at 2Bw and minima at 3Bgk horizons (Cruz-y-Cruz et al. 2014, Figure 1). These maxima and minima correlate well with the maximum and minimum values of Fe_d in the SRP paleosol. The correlation is owing to pedogenesis, which commonly leads to the formation of ferrimagnetic minerals, such as

magnetite, causing an increase in Fe_d and accordingly in K .

The situation in BOP is far more interesting. Horizon C has highest K , while horizons 3A and 3C present least K (Cruz-y-Cruz et al. 2014, Figure 1). As expected, horizon 3C has low Fe_d. In contrast, horizons C and 3A present a reverse correlation between K and Fe_d, with very low and mid-levels of Fe_d, respectively. This reverse correlation is owing to the production of ferrimagnetic minerals by the intense burning in ovens. In agreement, Carpenter et al. (2015) suggest that the ancient group built over 1,500 ovens in the area.

In summary, the study of K allowed identification of anthropogenic ferrimagnetic phases, which consecutively revealed the probable location of ancient ovens (Cruz-y-Cruz et al. 2014).

Case study 2: Source of multiperforated Olmec artifacts

The Olmec arose and flourished on Mexico's southern Gulf Coast between 1800 and 400 BC, and developed extensive trade relationships for procurement of exotic materials from distant regions. Magnetic susceptibility was used to determine the source locality of archaeological artifacts which Olmec society used as drill bearings (Alva-Valdivia et al. 2017). About three tons of the multiperforated artifacts were found at the archaeological site of San Lorenzo in southern Veracruz, Mexico (e.g., Cyphers and Di Castro 1996; Di Castro 1997). The artifacts are small and roughly cuboidal, with 2- to 3-cm-long edges. The artifacts have flat to slightly convex faces and rounded edges (Alva-Valdivia et al. 2017, Figure 2). Each artifact has three intentionally drilled conical perforations that developed when the artifacts were used as drill bearing.

The artifacts are comprised of iron ore. To determine the source of the artifacts, their rock magnetic properties (thermomagnetic and hysteresis curves) are compared with similar rock types exposed in the vicinity (several hundred kilometers) of San Lorenzo. These exposures are (1) Huitzo, Oaxaca, located in the Etla Valley; and (2) the volcanic-plutonic metamorphic complex of southeastern Chiapas in Motozintla.

Notably, the cooling and heating branches of the thermomagnetic curve of the Olmec and Huitzo samples are very similar, both partly reversible and partly irreversible (Alva-Valdivia et al. 2017, Figure 9). In contrast, the shape of the Motozintla curves (heating-cooling) and the range of magnetic susceptibility values are different from the Olmec artifacts (Alva-Valdivia et al. 2017, Figure 2). The wasp-waisted hysteresis curves are symmetrical for all samples and show a strong paramagnetic contribution. The Olmec and Huitzo samples have a remarkably high magnetic moment. Moreover, the two curves have very similar shape, in contrast to the Motozintla samples. Therefore, it is concluded that the Olmec artifacts are related to the Huitzo, rather than the Motozintla.

Case study 3: Archaeointensity dating: mineral phase changes in clay artifacts during heating

The importance for archaeological research to discern the chronological succession of events within the social dynamics of past populations is well recognized, because this knowledge allows understanding of the diverse social processes. Radiocarbon dating is the most common method to determine the age, if archaeologists can find the proper material to be analyzed. Alternatively, since the 1980s, archaeomagnetic dating started to be successfully applied. This method is characterized by age estimation in a high-precision confidence interval (combination of precision and accuracy). Besides, the determined age is related to an object or event of cultural importance that constitutes its great sturdiness.

The archaeointensity method is based on the fact that the magnetic minerals contained in clay acquire a thermal remanent magnetization when these are cooled in the presence of a magnetic field, after being heated to high temperatures. These temperatures reach the Curie temperature of the minerals, which depend on the cooking method for the ceramic.

To reach acceptable values of archaeointensity, it is essential that the artifact does not change its mineralogy during the heating

processes (one of the quality criteria that should be accomplished before attempting the extremely sophisticated archaeointensity experiment). Then, the thermomagnetic curves reveal the possible mineralogical changes. In the best-case scenario, they should be reversible during the heating-cooling branches, thus assessing that no changes in mineralogy are produced. After confirming a unique magnetic component during the thermal demagnetization processes in the artifact (another important quality criteria), it is almost certain that the archaeointensity experiment will successfully provide a reliable value of the intensity of the magnetic field at the time of the last heating of the artifact. Finally, comparison of these values with the secular variation curve of the magnetic intensity of the region (1,000-km-diameter area) reveals the age of the last heating.

Consequently, in many cases the archaeomagnetic ages will be much more useful than others. Therefore, archaeological ages will supply a scheme of the sequence of events at a single site or in a single region. Thus, the capacity to provide information with respect to stability and changes in the cultural and natural parameters through time is particularly important.

SEE ALSO: Electrical Resistivity; Electromagnetic Conductivity; Ground-Penetrating Radar; Magnetic Field Gradient; Magnetometry

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Magnetometry

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Magnetometry is the detection and study of archaeological deposits using instruments known as magnetometers (Figure 1), which record in units of nanoteslas, or nT for short. Magnetometers are useful for detecting objects, especially those made of iron, and various types of archaeological features that magnetically contrast with the sediments that surround them. Other metals such as aluminum, lead, silver, and gold are not magnetic. Understanding magnetometry and its application in archaeology can be broken down into three subtopics: magnetism, magnetometers and how they work, and the magnetic characteristics of archaeological sediments and features.

Magnetism

Magnetic fields have direction and magnitude, and they are often depicted as contour maps and as lines with small arrows indicating direction. The Earth's magnetic field is much like that of a bar magnetic, with north and south poles. Its direction and strength varies considerably depending on location. At the north and south poles the magnetic field lines are nearly vertical, while around the equator they are horizontal. In Figure 2 (top), the angled lines represent the Earth's magnetic field, which in this case is angled downward steeply. When two different magnetic fields intersect, they combine to either cancel each other out or increase or decrease the overall magnetic strength at that location. Iron objects, certain kinds of rocks (e.g., basalt, an igneous rock) and intensely heated iron-rich sediments (e.g., the bottoms of hearths) all have their own magnetic fields. These distinct magnetic fields combine with that of the Earth to create a total field strength. In the Figure 2 image (bottom), the magnetic fields of several different materials

are shown as distinct from the Earth's field for the sake of illustration. In reality, they would be combined with the Earth's magnetic field, creating localized magnetic anomalies that can be detected by a magnetometer. The magnitude of the Earth's magnetic field varies as well, ranging from about 30,000 nT to 60,000 nT depending on location (Lowrie 2007). This can vary daily by up to 100–200 nT due to the influence of charged particles ejected from the sun. These geographic and daily sources of magnetic variation are important to account for since archaeological features typically are quite weak in comparison, ranging from 1 to 100 nT in strength. And on some sites, significant features have been detected down in the 0.1–0.01 nT range.

There are two kinds of magnetization detectable with a magnetometer: thermoremanent magnetization and magnetic susceptibility. When iron-rich sediments and rocks are heated above a certain temperature, known as the Curie temperature (ca. 500–700 °C) (Lowrie 2007), they can become permanently magnetized—what is known as thermoremanent, or permanent, magnetization. At temperatures below the Curie point, an iron mineral's magnetic alignment is fixed. Once the mineral's temperature is high enough, its magnetic alignment is free to change and it becomes realigned to the strongest magnetic field in the area, which usually is the Earth's magnetic field. Campfires and trash burning can produce more than enough heat to reach the Curie point. Intense heating can make an otherwise magnetically neutral (i.e., minerals with random magnetic alignments) patch of ground highly magnetic through magnetic realignment; it can also transform less magnetic iron oxides (e.g., hematite) into more magnetic types (e.g., magnetite and maghemite). The resulting changes in magnetism are long lasting. Even sediments that have been disturbed and redeposited, such as by sweeping, plowing, or other kinds of earth moving, can maintain at least some of their permanent magnetization, which is not reset until the sediments are once again heated up to a point above the Curie temperature. Objects and sediments that are permanently magnetic do not

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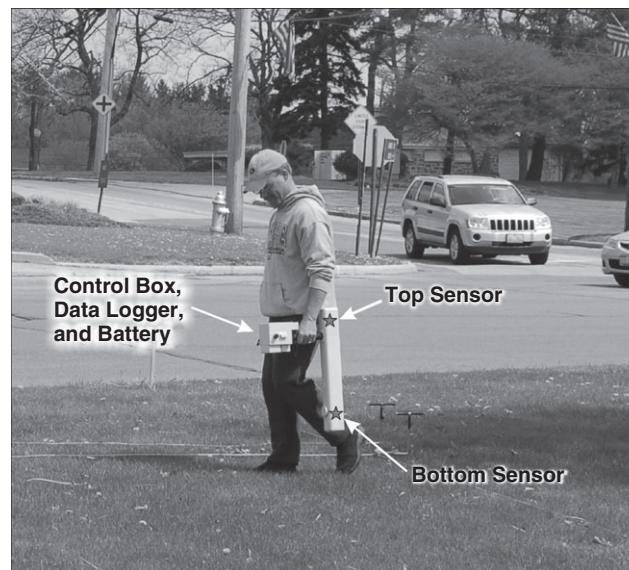


Figure 1 Components of a magnetometer, in this case a fluxgate gradiometer. Gradiometers record the difference between their two sensors, which helps to (1) filter out daily fluctuations in the Earth's magnetic field, and (2) lessen the influence of strong magnetic fields nearby.

require the presence of an outside magnetic field to be detectable, unlike those materials that are magnetic because of their magnetic susceptibility.

Soils and magnetic substances that have high *magnetic susceptibility* react when they are in the presence of a magnetic field. On archaeological sites it is the Earth's own magnetic field that causes these magnetic reactions. Certain soil horizons and components of soil, such as organic-rich topsoil (A horizon), are generally more susceptible to magnetic fields than deeper soil horizons, such as Bt (i.e., subsoil) horizons (Evans and Heller 2003). This can be a very useful principle on many kinds of archaeology sites, where the most common kind of archaeological feature is the pit feature—a hole dug into the ground that has been filled with topsoil or site midden and refuse. The Earth's magnetic field tends to be stronger in features with elevated susceptibility (as in the earth oven in Figure 2) and it is weaker in materials with low susceptibility (such as the limestone foundation stones in Figure 2). Furthermore, human occupation of an area enhances a soil's magnetic susceptibility (Dalan and Banerjee 1998). While the mechanisms behind enhancement are complex and

not totally understood, bacteria that use and produce small magnetic particles contribute to the process (Fassbinder, Stanjek, and Vali 1990), as well as burning and the amount of certain iron oxides present in the soil (Evans and Heller 2003; Graham 1974).

Magnetometers

Magnetometers were first used on archaeological sites in England in the 1950s (Aitken 1961). It was not long before their use spread into other parts of Europe and over to the United States (Black and Johnston 1962; Herbich 2015). All magnetometers consist of the same general parts: (1) magnetic sensor(s) and (2) a control unit that runs the instrument, has a data display or settings interface, records data, and contains the batteries (Figure 1). There are several types of magnetic sensor, with unusual names such as proton free-precession, electron spin-resonance (Overhauser), and alkali-vapor (Optically Pumped) (Aspinall, Gaffney, and Schmidt 2008; Lowrie 2007). Perhaps the most common sensor type now used in archaeology

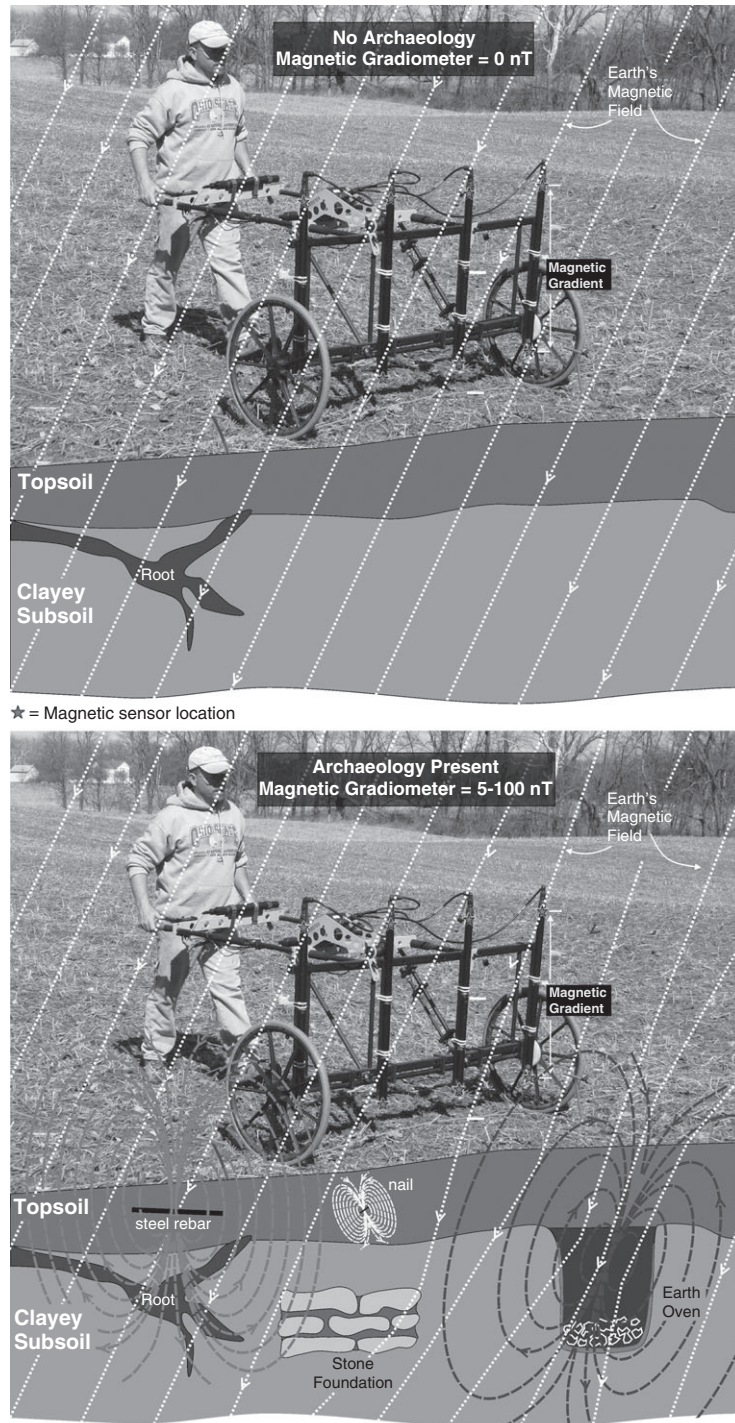


Figure 2 Illustration of the Earth's magnetic field (top) and the shapes and sizes of the magnetic fields of objects and archaeological features (bottom). Magnetometers, which are passive devices, can only detect subsurface features or objects that influence the magnetic field at the height of the instrument's sensors.

is the fluxgate sensor. Usually, two are paired together as a fluxgate gradiometer—the latter term indicates that this type of magnetometer records the difference between two sensors, which helps to filter out the daily fluctuations in the Earth’s magnetic field. Fluxgate sensors are highly sensitive to direction and must be aligned, in effect zeroed out, in all directions. Other magnetic sensor types, such as the commonly used Cesium Vapor type, detect the “total field” and are unaffected by the direction of survey.

As in most geophysical surveys, a magnetometer survey is conducted by moving an instrument back and forth across the site in parallel lines,

or transects, while the instrument records the magnetic values at a set rate. Four to 16 samples per meter along transects spaced 25–100 cm apart are common data densities. Most instruments simply record strings of numbers as the surveyor collects the data in a gridded pattern. Coordinates are assigned to each data value upon download (Figure 3, upper left). Modern magnetometer systems are now synched with precise global positioning systems (GPS) and each magnetic value is recorded with a geographic coordinate. Once they are downloaded, magnetic data often require processing to remove defects caused in data collection, such as striping due to running a

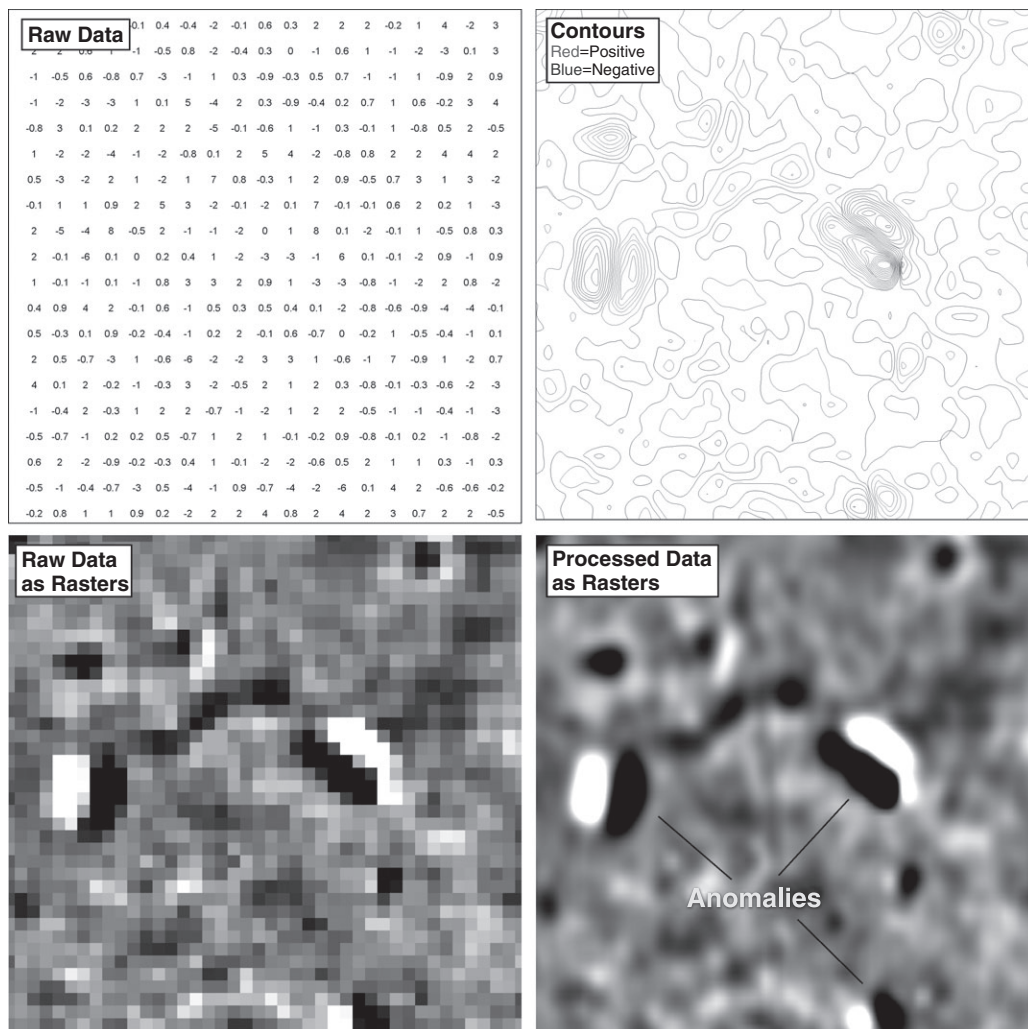


Figure 3 Magnetometry data visualization examples.

fluxgate gradiometer in two different directions. Interpolation can be used to boost data density, to a degree, and highlight smaller anomalies. Finally, image processing filters, such as the low pass filter, are used to minimize the small variations caused by subtle differences in the near-surface soil.

There are several ways to visualize magnetic data. A simple plot of the magnetic values at the locations where they were recorded is cumbersome, especially for large surveys (Figure 3, top left). Using contour lines to indicate trends across the data is useful in small survey areas, but this becomes overly complicated with large surveys and those with many anomalies. Even better is converting the values to cells, or rasters, that are colored according to the magnitude of the recorded magnetic value. Grayscale displays are most common for magnetic data; in the United States and other parts of the world, positive magnetic values are black and negative are white.

Magnetometry in archaeology

Magnetometry is the most popular of the geophysical survey techniques used in archaeology. It can be fast—GPS-enabled magnetometer arrays with probe spacings of 25 cm can cover over 12 hectares per day; smaller, single probe systems can cover half a hectare in a day. And whether small or large in extent, magnetometry surveys detect a wide range of feature types.

The effectiveness of magnetometry for finding features on archaeology sites depends on many factors, including soil type; the depth, size, and composition of the feature; and the magnetic data density. To be detected, a feature must stand out magnetically against the background magnetic levels of the site. Figure 4 exhibits a range of magnetic feature types. While there are many kinds of archaeological features, most can be characterized as cut or surface features. The most common are cut features, which are excavated down into the ground and include pits for burial,

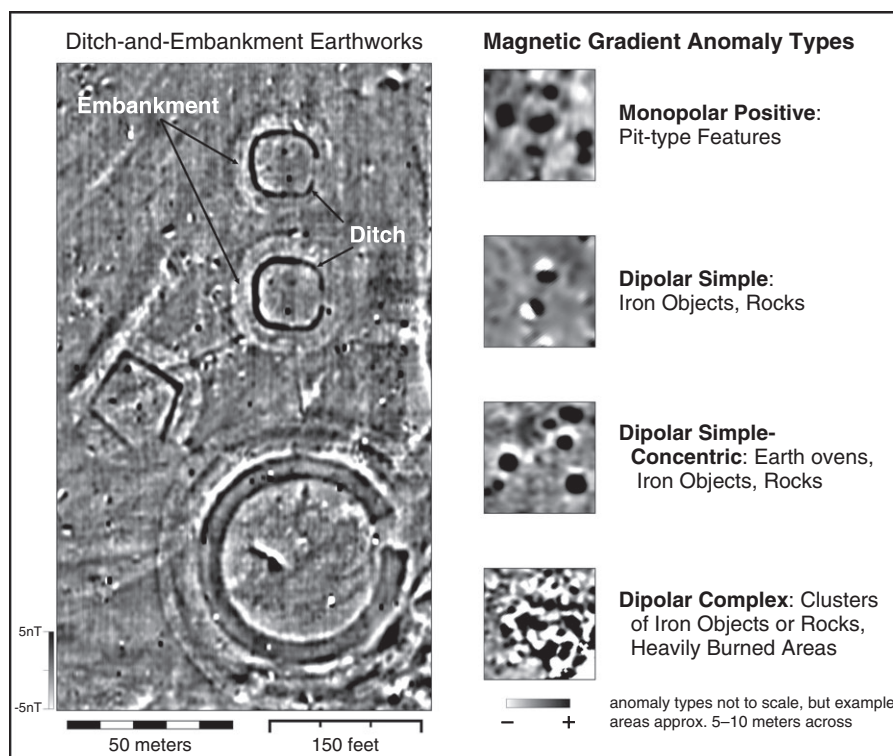


Figure 4 An example of magnetic gradient anomaly types useful for archaeological sites in the northern hemisphere.

storage, and refuse disposal. In the northern hemisphere, these tend to appear in magnetic data as small positive anomalies (Figure 4). The accumulation of topsoil or magnetically enhanced archaeological midden in pits elevates their magnetic susceptibility. When pits are filled with burned sediment or certain types of rocks, they sometimes produce dipolar anomalies, similar to a weak bar magnetic buried on end. Iron objects and magnetic rocks are fairly distinctive in magnetic data as they produce dipoles, with positive and negative sides. Complex archaeological deposits, such as those containing a mix of iron objects, magnetic rocks, and burned sediment, can produce clusters of positive and negative anomalies. Linear features, such as foundation walls, earthen embankments, and filled ditches, are often the most readily identified features when detected. Though some interpretations of magnetometry data are obvious, verification through coring or excavation (often referred to as “ground-truthing”) or survey with additional instrument types can improve interpretations.

SEE ALSO: Airborne Remote Sensing; Archaeomagnetism; Electrical Resistivity; Electromagnetic Conductivity; Ground-Penetrating Radar; Magnetic Field Gradient; Magnetic Susceptibility; Radar; Visualization of Magnetometer Data

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Marine Excavation

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“Marine excavation” as a topic can have a variety of meanings, and obviously the excavation of an area of seafloor can have a multitude of purposes ranging from archaeological investigation to the dredging of shipping channels, dock, pier, and bridge construction, and other types of applications. Even within the topic of scientific diving, marine excavation is conducted in a number of contexts. These can include excavation of shipwrecks, aircraft, submerged archaeological sites, sediment sampling for biological/environmental analyses, or dry-land excavations on wrecked or abandoned vessels that now lie under land (for an extreme version of this latter context, refer to the steamboat *Arabia* in Hawley 2005). For the purposes of this entry, marine excavation will refer to the excavation of submerged archaeological sites in an underwater context, as land excavations on non-wet shipwreck sites utilize rather standard methods of terrestrial excavation.

Before delving deeper into the topic, some consideration must be made as to the reasons for excavation, as this is a destructive process. Even if removal of sediments is not inherently harmful to the specific site being studied, removal of artifacts, features, and other aspects of the material culture of the site precludes these items from ever being returned exactly in their original context. Generally, broad-scale excavation only is considered justified after the creation of a research design in which careful consideration of survey, testing, and excavation strategies is outlined. A valid research design could include a literature search for previous studies related to the site, a clear statement of project objectives and methods to be used for each phase of the project, sources of funding, the timetable for fieldwork, analysis, conservation, and publication, considerations of crew requirements and support, and a safety plan (specifically a dive safety plan).

Doing scientific fieldwork underwater presents many complications and challenges, and safety should remain paramount throughout the project. The underwater environment must be an uppermost factor in planning the research project, as it affects nearly all aspects of the fieldwork. How deep is the site (how much bottom time is each dive team going to have on the site)? Are there tides/currents that will affect fieldwork? What is the water temperature? Will divers need wet suits or dry suits, or additional training on the specific techniques employed in working on the site? How much visibility is there on the site? Is there dangerous marine life? Where is the nearest recompression chamber? These are just some of the basic questions that should be considered when planning underwater fieldwork.

No underwater archaeological research project should move forward without a coherent plan and funds for conservation of the finds that will be generated from the excavation, as well as storage space and a collections management plan for any artifact collections that may be generated from the project (for project planning considerations see UNESCO 2001, Convention on the Protection of the Underwater Cultural Heritage, rules 9 and 10). Due to the complexity and cost of broad-scale maritime archaeological excavations, there is a growing trend toward noninvasive techniques and the principle of in-situ preservation as the preferred approach to studying submerged sites as finite, nonrenewable resources (see Bowens 2009, 135–136). When, however, the above topics have been considered and a proper research program has been designed, and archaeological excavation is the only way to move forward, there are various aspects of marine archaeological excavation at our disposal.

As the specialized field of maritime archaeology developed, a variety of methods have been devised for removal of sediment from submerged sites. These range from low-tech options such as hand fanning, manual digging using specialized hand tools, to mid-level techniques including water induction dredges, air lifts, and water jets, to larger, industrial-level systems such as dredge

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barges and other types of heavy machinery. It is impossible to summarize the range of approaches and techniques that have been used over the years and during countless projects for the removal of sediments from underwater sites, but several standard methods have been utilized in multiple contexts and will be presented here. During this discussion, the author may describe specific techniques or examples utilized by scientific divers at the University of West Florida (UWF), but it should be remembered that there are usually several good approaches to site excavation, and there may be other methods that work just as well.

Of the various “low-tech” methods, the human hand can be considered the most basic approach to removal of sediments underwater (Muckelroy 1978, 24–36). Whether hoping to gain a glimpse of the source of a remote sensing anomaly, or “dusting” the surfaces of pre-exposed timbers to expose details such as wood grain or fastener patterns, hand-fanning can be an effective way to move small amounts of sediments in a careful, controlled manner. This method is free, always available, and in low visibility our divers often take off one glove, or utilize fingerless gloves, to allow greater sensitivity when going through the soil matrix. Using your hands to direct sediments toward a dredge or other sediment removal system can be very effective as well, and if, for example, the hose of a water induction dredge could be considered the “shovel,” hand-fanning could be considered the “trowel,” allowing the skilful diver to remove individual grains of sand if need be while keeping the dredge lifted away from the feature being excavated. Along with hand-fanning, any number of extraneous tools have proven their worth during underwater excavation: some that have been useful to us at UWF include trowels (the same kinds used on terrestrial sites), brushes, spoons, dental tools, plastic/bone folder tools, plastic spatulas, dust pans, cups, and buckets. Small-mesh bags with secure drawstrings and a clip to allow you to secure these tools to your dive gear are indispensable for managing these implements while diving. In short, when faced with a particular problem in low-tech sediment removal, a trip to the local hardware store can lead to creative solutions for marine excavation.

If hand-fanning is not sufficient for adequate excavation of a site, then various other methods of mechanical removal of sediments have been developed and adapted for maritime archaeology. Two common techniques involve incorporating suction dredges to remove sediments to screening stations, exhaust bags, or disposal/spoil areas away from the site. On sites with sufficient depth, the use of airlifts has proven beneficial and not overly complicated. The principle here is to inject air from a surface compressor near the bottom of the lift (a tube or pipe) in a controlled manner, which will then force the discharge end of the lift in a close to vertical orientation. As the air injected into the bottom of the lift rises, decreasing pressure causes it to expand, creating suction at the bottom end of the lift. There are numerous variables involved in making any mechanical suction system work sufficiently, such as tube/pipe diameter, output of air compressor, and number of airlifts used. Some airlifts need to be anchored at their suction end due to buoyancy generated through the air being injected into the lift. A crucial consideration with airlifts is water depth: typically they work best when there is at least one-half to one atmosphere of pressure difference between the bottom sediments being excavated and the surface (around 5–10 m), though they have been used successfully in shallower waters with less efficiency (Green 2004, 252–256). In significantly deeper waters, a compressor with enough force to push air to the bottom of the pipe/tube is required, which can affect the project budget as these tend to be expensive, and also requires a sizeable research vessel or diving platform for operation. Another factor to consider is where the spoil exiting the exhaust end of the lift is being directed to: If collection and screening of spoil is desired in the case of small finds being excavated in the dredge spoil, then a screen or similar means for sifting through the spoil can be fitted to the end of the lift. Alternatively, the airlift can be arranged to exhaust spoil to a surface screen or collection point. The pipe/tube should be situated so that material exiting the airlift can flow down-current if possible, to avoid dumping excavated material back on site and affecting diver visibility.

A second means of creating a suction dredge involves pumping water, rather than air, through hoses to a suction nozzle, commonly known

as a water induction dredge. As with airlifts, there are many variations in this design, and some are commercially available through gold dredging suppliers and other industrial sources. The basic operation requires a water pump, and for shallow water excavation UWF archaeologists use a 5.5-horsepower pump with 7.6-cm (3-inch) hoses/fittings. A semi-rigid intake hose allows water to be sucked into the pump, which is then transferred through the pump's outflow to a collapsible hose that extends to the suction nozzle, which typically lies on the seafloor near the site being excavated. The hose attaches to the nozzle at an angle, so that the force of the water entering the nozzle is directed to the exhaust end of the system. This creates suction at the open end of the nozzle, which is often fitted with a flexible hose that divers can manipulate during excavation. This system has several advantages: It is relatively cheap to design (UWF archaeologists construct their dredges with PVC pipe) and can be used in shallower water than airlifts; the water pumps are typically cheaper and lighter than compressors, and can often be deployed on small craft; and the fact that the dredge lies on the seafloor reduces turbidity (the amount of material being introduced into the water column), which can affect the environmental impact of the operation, and may be an issue depending on permits and agencies overseeing the research project.

Methods mentioned above have successfully been implemented on remotely operated vehicles (see Søreide 2011). Other, more industrial means of sediment removal exist, including very powerful airlift and induction dredge designs implemented from barges, cranes, or other large support vessels, or removal of sediments by construction equipment such as clam-shell grabbers and other machines. At this scale, scientists usually work closely with professional construction managers or engineers in order to conduct the project, and specific situations vary immensely. At the very least, however, consideration and careful planning should go into issues such as safety and the proveniencing of artifacts uncovered during such operations, as the archaeological context of the site remains paramount.

Other considerations with using any kind of mechanical excavation equipment include safe handling by divers. At UWF, new scientific

divers go through a week of training prior to any fieldwork, where they review all of their open-water diving skills, as well as learn how to set up dredges and move heavy equipment, first on land, then underwater in the pool, and finally in the murkier waters of Pensacola Bay, all under supervised, controlled conditions. This type of specialized diving goes beyond what is taught in most basic open-water SCUBA classes, and every project should go over protocols and how to operate the machinery specific to that project, regardless of how experienced the field crew may be. Potential hazards from using the kinds of equipment mentioned above might include: inadvertently sucking up part of the diver's equipment into the dredge or injuring one's hand in the dredge (a shut-off valve or system for shutting off the dredge from the surface should be implemented); uncontrolled ascents when air is introduced into a system component such as an airlift; uncontrolled descents when passing off heavy excavation gear to divers in the water who are unprepared for the added weight to their buoyancy; and low visibility conditions, when dredging disturbs bottom sediments and divers can experience "black out" conditions, to name just a few.

Provenience is a final issue that should be mentioned. Establishing artifact context in three dimensions, or "XYZ" format, is a basic requirement for archaeological fieldwork. This can be done in a variety of ways, but often a grid system is established on the seafloor prior to excavation, and any finds, features, or hull remains are mapped in relation to this grid system (Green 2004, 237–240). This is also effective in proveniencing any small artifacts inadvertently sucked up the dredge during periods of low visibility. Regardless of how careful the diver is, small finds such as bones, beads, and fasteners may be removed by the dredge on accident. Having a means of gathering dredge spoil (we use double-mesh bags attached to the exhaust of our dredges) allows for the collection of this material, and utilizing a grid system provides locational data for where the objects came from on the site. UWF divers utilize a rigid aluminum grid, composed of 1-m lengths connected to six-sided "stars," or corner joints that allow the 1-m lengths of aluminum shafts to form a $1 \times 1 \text{ m}^2$, with a vertical shaft allowing longer lengths if needed

for vertical support. These horizontal and vertical shafts then can be secured with zip ties or thumb-screws. The flexibility of this system is that it can be created on an as-needed basis, starting with a 1×1 or 2×2 , and then can be expanded by dive teams adding more material to the grid system. Plastic tags marked with unit designations are affixed to the northeast corner (this is arbitrary, but should be standardized as to the best location for the specific site), so that even in low visibility divers can easily navigate to the current unit being excavated. There are many other ways of establishing provenience, so this should be a clear part of the research design and considered of paramount importance for excavation activities.

SEE ALSO: Field Survey

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Mobile Geographic Information Systems (MGIS)

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Mobile geographic information systems (MGIS) are a framework that combines spatial and non-spatial data within a mobile platform for field data collection and mapping. MGIS tools have been fervently adopted by many field archaeologists in recent decades and have become an essential component in the process of recording cultural resources in government, academic, and cultural resource management (CRM) settings. Due to the rapid pace of development and improvements in mobile data collection devices, batteries, and global positioning system (GPS) technology, archaeologists now have an abundance of MGIS hardware and software to select from and have the ability to tailor these solutions to meet ever-changing project requirements. As more and more components of archaeological fieldwork move to a born-digital form, MGIS systems play an essential role in linking spatial data within archaeological contexts to nonspatial data, including photographs, field notes, regulatory forms or paperwork, and other textual data. Linked and combined together, these datasets can quickly and efficiently aid and inform archaeological analysis and interpretation without the laborious, and sometimes error prone, digitization and transcription efforts required in the past.

MGIS frameworks developed concurrently with the widespread use of desktop computer-based GIS in archaeology, as GIS databases became the de-facto digital data warehouse for spatial archaeological data. Early MGIS platforms required large data collection hardware, including laptop, mobile, or handheld personal computers (PCs) linked to external GPS

receivers. These initial hardware and software systems, however, could be large and cumbersome, and were therefore slow to be adopted in most archaeological fieldwork situations (Wallrodt 2016).

As a result of rapid improvements in mobile computing, more recent MGIS hardware is smaller and more portable, and can run for hours, or even days, on a single battery charge. These devices, including cellular phones, tablets, and laptops, can include large sunlight-readable touch screens and are often ruggedized and weatherproof in some form. Newer devices include integrated mapping-grade GPS receivers, or can be linked to any number of high-accuracy external GPS systems via cables or Bluetooth. Additionally, through post-processing or via mobile communication links to virtual reference stations (VRS), high accuracy differential GPS (DGPS) systems (see GPS (GLOBAL POSITIONING SYSTEM)) may provide centimeter or better spatial accuracy to any number of MGIS hardware and software solutions.

In combination with mobile wireless, or cellular connectivity, many MGIS hardware systems can be linked back to the laboratory or office for a real-time review of archaeological field crew progress. Archaeological data can be immediately stored in desktop or web-based GIS databases for analysis, interpretation, and reporting before fieldwork has been completed. However, given the remote nature of some archaeological fieldwork, real-time updates may not be possible or could be subject to expensive mobile data plans in many regions of the world. In the absence of wireless data transfers, physical backups via external storage cards should be considered to prevent data loss. Further, remote field conditions may require additional batteries or other means of charging MGIS hardware. These power sources may include solar charging systems, external battery banks, or portable gas-powered generators.

A variety of proprietary MGIS hardware systems are available to archaeologists, manufactured by large geospatial companies such

as Trimble, Leica, Garmin, and CHC. These all-inclusive devices include internal GPS receivers and, while some systems require post-processing to improve locational accuracy, many deliver real-time sub-meter or better solutions with satellite-based augmentation systems (SBAS) or VRS. A limiting factor to these proprietary systems is that the archaeologist is often tied to manufacturer-specific software such as TerraSync, ArcPad, or SurvCE. Using this software, the archaeologist may have very little control over data dictionary design, data collection workflow, and interoperability. These software programs may also require specialized vendor-provided training and expensive maintenance contracts. However, a large number of MGIS hardware devices are now available that are based on Android-based operating systems, or can pair via Bluetooth with any number of Android or iOS tablets or mobile phones. This advancement opens up the MGIS data collection workflow and allows the user to use any number of open source, or custom designed and developed, data collection applications.

Various MGIS software solutions exist for archaeological fieldwork applications. Commercial, and often proprietary, software includes Esri ArcPad, ArcGIS Collector, Trimble TerraSync, Carlson SurvCE, Leica MobileMatriX, Fulcrum, and Filemaker Pro. Depending on the project's chosen hardware platform, free and open source software is also available for MGIS data collection, including Open Data Kit (ODK), SurveyCTO, QGIS Mobile, and FAIMS Mobile. Installed on Android-based systems, these software applications can easily be paired with high-accuracy Bluetooth GPS receivers from a variety of manufacturers with a range of advertised accuracies, including the Bad Elf (1–3 m), Trimble R1 (60 cm), SXBlue III (1 cm), and EOS Arrow (1 cm).

Nearly all of these software solutions, both commercial and free or open source, allow the field archaeologist to load predefined data dictionaries or database schemas, project areas, recent satellite imagery, georeferenced historical imagery, or custom basemaps prior to the start of MGIS data collection. In addition to acting as a basic navigational aid, these datasets allow the archaeologist to make better informed decisions when undertaking new survey or excavation

projects. In some cases, paper forms can be digitized prior to fieldwork and these attributes can be linked to point, line, and polygon GIS data collected in the field. Additionally, depending on the nature of the project, the process of preloading spatial information into MGIS software can allow the archaeologist to ground-truth and record archaeological features, or other areas of interest, identified through imagery or model-based analysis in the laboratory (Tripcevich 2004). Once in the field, many devices allow the user to sketch archaeological features, profiles, and other objects of interest with a digital pen or stylus that can be used in subsequent analysis and reporting. All software generally includes the ability to view data already collected on a project, and make changes to extant data or append additional data before fieldwork concludes.

With a carefully designed data collection strategy in place, digitized field forms can be readily integrated and combined with MGIS spatial data after fieldwork. This provides considerable time savings over past practices that required the often tedious process of transcribing field notes and other data entry work. Additionally, born-digital data reduces transcription errors, and improves data reliability, consistency, and interoperability. Collected within a holistic MGIS framework, data that once may have existed in isolation, such as photographs, data tables, and field notes, can provide an interactive reference for analysis, interpretation, and reporting. In this form, the process of data sharing is greatly simplified and collaboration becomes a more fluid process. Further, within a relational database, all field data, form data and attributes, locational data, and photos can be linked for use within a desktop GIS application (ArcGIS, QGIS) or hosted on a web-accessible database for presentation on any number of web-based mapping applications.

To date, MGIS has been adopted widely by archaeologists in pedestrian survey, reconnaissance, and excavation contexts around the globe (de Roo, Bourgeois, and De Maeyer 2013). In excavation projects, MGIS devices have been used for artifact cataloging and tracking when combined with portable, battery-powered barcode printers (Parker and Eldridge 2014). Custom software and database applications have been developed for MGIS in archaeology, including

FAIMS, ArcheoLINK, and the Archaeological Recording Kit (ARK). These applications provide a framework for collecting, storing, and reviewing both spatial and textual archaeological data and, after undergoing training in software development, the archaeologist can often customize these applications to meet any number of research requirements.

MGIS will remain even more relevant moving forward as archaeological fieldwork continues to require the collection of more and more spatial data and other digital information. Digital data collection may become even more critical within regulatory environments that emphasize nondestructive and noninvasive archaeological investigations. However, some archaeologists may encounter a number of problems when striving to meet these challenges. As more and more research designs call for the collection of very large spatial datasets, including those acquired through light detection and ranging (LiDAR) (see TERRESTRIAL LIDAR) or unmanned aerial vehicles (UAVs) (see DRONES), or generated through photogrammetric processing (see PHOTOGRAMMETRY AND STEREOPHOTOGRAMMETRY) in addition to that of traditional field recording, data storage and management can become problematic. Furthermore, without careful planning, MGIS datasets can become isolated from their larger context and may remain unavailable for sharing and integration (McCoy and Ladefoged 2009). To avoid this, prudent consideration should be given to data storage, database management, and database design before undertaking such projects. These approaches require a well-researched, holistic approach to data collection with a solid, yet flexible and expandable, database design. Ample resources need to be provided for data storage plans, backups need to be performed regularly, and, to prevent unintended data manipulation or destruction, data versioning should be implemented when possible. Additionally, archaeologists, particularly those with supervisory roles, need to be provided with professional development opportunities and any other necessary training that teaches appropriate MGIS data collection practices.

Future MGIS systems may allow for the ability to perform spatial analysis, such as kriging or other density analyses, while in the field to identify artifact or feature concentrations that

inform subsequent testing, sampling, or excavation. Additionally, with some training, the development of MGIS systems can provide an exciting starting point for the sharing of custom archaeological applications, digitized field forms, and other collaborative products through the use of source code sharing websites such as Github. Given further improvements in hardware and software development, research and collaboration, and real-world testing and implementation, MGIS will continue to be a highly relevant tool for documenting and understanding cultural resources.

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Photogrammetry and Stereophotogrammetry

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Historical perspectives on photogrammetry and stereophotogrammetry

Closely following the invention of photography in the mid-1800s, stereophotogrammetry emerged as the science of extracting metric data from pairs of still photographs. Although commonly employed and developed by governments for civil and military purposes (often using aerial photographs), it was not until the 1970s that archaeological publications employing photogrammetry became routine. Early applications in archaeology often featured specialized pairs of fixed-base cameras with precise calibration to take stereopairs of photographs, although individual cameras could also be moved to achieve similar ends.

Early applications of stereophotogrammetry both facilitated the display of archaeological findings and aided in analysis. Subjects of study ranged in scale from engravings to monument complexes, and allowed linear and volumetric measurements to be made. Despite its acknowledged potential, in its earlier form the technology did not see widespread use by archaeologists; stereoscopic equipment was expensive and highly specialized, costing over six figures in the 1970s, and required a skilled operator. Some of these concerns were mitigated with increasing use of computers in analysis, although photogrammetry remained a relatively specialized tool into the early 2000s. While originally clumsy and inaccessible, early developments established both the conceptual and technological foundation for modern photogrammetry to progress.

Contemporary photogrammetry

More recently, a number of user-friendly software packages have been developed to process photogrammetric models from multiple source images (e.g., Autodesk's 123D Catch, Visual SFM, or Agisoft PhotoScan) in conjunction with almost any digital camera and computer workstation. Through application of computer-vision algorithms including structure from motion, or SfM, like points within a series of overlapping photographs are used to generate three-dimensional datasets and orient camera positions (see Green, Bevan and Shapland 2014 for a discussion of SfM). In addition to producing qualitatively and quantitatively accurate model surfaces, photogrammetric techniques facilitate the production of detailed, photo-realistic textures that surpass in quality the other modeling options. While technically complicated, in contrast to early iterations of the process, most software employed today simplifies the workflow in data processing for users, making it one of the best options available for archaeologists interested in producing three-dimensional datasets. The resulting models are easily disseminated via the Internet to facilitate remote research and outreach.

Compared with current applications of laser scanning (see LASER SCANNING), structured light scanning (see STRUCTURED LIGHT SCANNING), lidar (see TERRESTRIAL LIDAR, AIRBORNE LASER SCANNING AND LIDAR), or CT scanning (see COMPUTED TOMOGRAPHY), photogrammetry confers a number of benefits. Unlike those technologies, which require expensive hardware, software, and specialized technicians, photogrammetric setups cost only as much as a digital camera, and data can be collected by anyone who can take photographs. Open-source software for model building and free web platforms for display further add to the affordability and accessibility of photogrammetry to a wide range of users. Whereas these other technologies require a dedicated and stable power source and are comparatively difficult, if not impossible, to bring to most archaeological field sites, no such issues are encountered with photogrammetry. Digital cameras are easily trans-

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ported, charged, and used under most field conditions, and basic modeling for quality control can be completed in the field using laptops. Additionally, data collection can be significantly less time intensive compared with the other listed methods.

The strengths of photogrammetry also confer weaknesses that have been recognized for some time. Issues with operator skill and variation in model quality are more acute in photogrammetry than other technologies that have less mutable workflows and carry a higher price. Depending on the data-collection practices followed, this means that photogrammetric models of the same subject may vary considerably more than those made using other modeling options. Despite this, recent attempts to standardize workflows and suggest best practices have eliminated some of these issues, and it is expected that, with time, photogrammetrical routines will continue to be refined.

Photogrammetry has been utilized to create datasets from a number of different vantage points and scales. Across these scales, comprehensive best practices have been suggested to enable better accuracy and repeatability (e.g., Porter, Roussel, and Soressi 2016). Most frequently, the models are used in well-established forms of analysis already conducted by archaeologists: to take basic linear measurements, calculate volume, or to visualize and record changes in excavation surfaces through time, for example. These applications have been employed at a number of different scales with different image acquisition and modeling routines: from small artifacts photographed on turntables, to entire landscapes captured by unmanned aerial vehicles. In addition to using photographs taken explicitly to produce photogrammetric models, researchers have also used photographs collected historically, or through crowdsourcing, to generate 3D models of heritage objects (see *DESIGNING AND CO-CREATING HERITAGE*) that has been destroyed due to natural disaster or conflict (Grün, Remondino, and Zhang 2004).

Object-based photogrammetry

Archaeologists have modeled individual objects, ranging from stone tools and ceramics to larger

stone carvings. Working with smaller subjects gives photographers the option to control their data-collection parameters, including light and camera settings, which has been shown to impact qualitative results (Magnani, Douglass, and Porter 2016). In cases where objects are small and appropriate materials are available, placing the object on a turntable permits photographers to leave their cameras in fixed positions while the object is rotated. This permits more stable, regularized photographs to be taken (Porter et al. 2016). In most cases and with larger objects, however, a camera's position is physically moved around the artifact. The method is particularly suitable for gathering field data in cases where time is limited and artifacts cannot be collected. For the smallest subjects, studies have indicated no significant differences in measurements between traditional caliper measurements and photogrammetric models, and model quality is noted to produce textures of sufficient detail to permit the observation of important elements of artifacts (e.g., raw material, flake scar direction in the case of stone tools). Other works have demonstrated the utility of the technology to model surface modifications on individual objects, like cut marks made with different tools on bone (Maté-González et al. 2016). Basic linear, volumetric, and geometric morphometric (see *GEOMETRIC MORPHOMETRICS*) measurements may also be taken using photogrammetrically-derived three-dimensional models.

Ground-based photogrammetry

Ground-based features and excavation surfaces have also been modeled. Unlike working with smaller objects that are frequently photographed indoors, working with larger, often outdoor subjects affords photographers less control over environmental parameters like lighting. However, the benefits of using such recording techniques have been emphasized in survey contexts where data collection for photogrammetry was faster to collect than line drawings for hearths, wells, and other features (Douglass, Lin, and Chodoronek 2015), and richer than data collected by total station measurements (see *TOTAL STATION*) for earthworks (Magnani and Schroder 2015).

Specific photogrammetry routines have been reported as less precise than total station measurements, although they can be used to visualize individual artifacts in situ. When conducted at regular intervals, models provide a detailed record of excavation progress and site stratigraphy. In many cases, ground control points (GCPs, or identifiable marks in known locations) are recommended to ensure accuracy, tethered to known coordinates which permits the orientation of the model in space (Green et al. 2014). For features, accuracy to approximately one centimeter is achievable. While most research has dealt with terrestrial subjects, general principles applied on land are also appropriate for use underwater, so long as distortion from water is taken into consideration.

Aerial photogrammetry

Photographs taken from airplanes, unmanned drones, kites, balloons, or even large camera booms have been used to generate topographical maps of landscapes, or other larger monumental archaeological features. Aerial photogrammetry allows for similar analyses to ground-based and object-based photogrammetry on a larger scale (for example, in showing the change in volume of larger excavation surfaces through time). Aerial photogrammetry provides an affordable alternative to lidar systems in particular, yet unlike other technologies, provides detailed photographic textures. Compared with measurements taken using total stations, the method provides a significantly faster way to generate elevation maps. Studies have emphasized the accuracy of the digital elevation models yielded from georeferenced aerial photography, between 0.14 and 0.31 meters (95% confidence interval), and models have even been generated using old pairs of stereophotographs from aerial surveys (Verhoeven, Taelman, and Vermeulen 2012).

Photogrammetry looking forward

In just the last decade, photogrammetry has become widely accessible to archaeologists. In this short time, the technology has already proven

itself as a useful and most accessible tool for those interested in creating 3D models ranging in size from individual objects to larger features and structures. As user-defined photogrammetric workflows and the software packages used to process photographs become better refined, the quality of models generated for archaeological analyses will continue to increase. Beyond improving archaeological analyses, photogrammetry has begun to show promise as a tool to communicate and engage with broader publics (Douglass et al. 2017), through a general democratization of access to archaeological subjects, and even by facilitating participation in projects through crowd-sourcing photos of lost heritage. However, while publications abound related to the use and development of photogrammetric techniques, the technology has yet to realize its potential in the hands of archaeologists; thus far, most publications have focused on proofs of concept and emphasized the use of the new technology to take traditional archaeological measurements more efficiently. Through future innovation in application, the technology will begin to reach its full potential.

SEE ALSO: Airborne Laser Scanning and Lidar; Designing and Co-Creating Heritage; Laser Scanning; Structured Light Scanning; Terrestrial Lidar; Total Station

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Portable X-Ray Fluorescence Spectrometry (pXRF)

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Introduction

Many methods of elemental analysis have been used on archaeological materials to address their overall composition or specific elements to identify the source of their geological components. Early in this millennium, however, non-destructive portable X-ray fluorescence (pXRF) spectrometers were commercially developed, allowing analyses to be performed within museums around the world, on virtually any size of artifact (Morgenstein and Redmount 2005; Cecil et al. 2007; Craig et al. 2007) (Figure 1). Early concerns about data calibration have largely been dealt with, while surface analysis of heterogeneous materials will always be limited to semi-quantitative results. Overall, the use of pXRF has led to large-scale studies of obsidian, ceramics, metal, and other materials, as well as studies on specific objects where elemental analysis simply was not previously possible (Tykot 2016). Just like any other analytical instrument, a pXRF user needs appropriate training and understanding of its principles, advantages, and limitations (Liritzis and Zacharias 2013; Shugar 2013).

Principles of X-ray fluorescence and pXRF

Energy dispersive X-ray fluorescence (ED-XRF) spectrometers measure the energy level and intensity of secondary (fluorescent radiation) X-rays produced by primary X-rays striking the sample and creating vacancies in an inner shell of the atoms, which are then filled by lower-energy electrons from an outer shell. The

energy difference between specific shells is fixed but varies between elements, so that secondary X-rays have a characteristic transition energy and thus may be attributed to specific elements. The strongest X-ray intensity results from an L-shell electron replacing a K-shell vacancy is called $K\alpha$, while an M-shell electron replacing a K-shell vacancy is called $K\beta$. The replacement of L-shell vacancies by M-shell electrons is called $L\alpha$ and by N-shell electrons, $L\beta$.

For both portable and regular ED-XRF spectrometers, energy level and intensity are measured by a detector, with the raw data calibrated using standards and appropriate software. The standards used for X-ray analyses must be of similar bulk material to the objects being analyzed, since the ability of the secondary X-rays to reach the detector is affected by the composition of the matrix. Calibration has been widely established for silicate materials including obsidian and many ceramics, but to a lesser degree for metals and other materials. Calibrated results are always necessary for comparing data from different analytical instruments (e.g., Goodale et al. 2012; Williams, Dussubieux, and Nash 2012).

The fundamental difference between regular and portable XRF instruments is the exterior location of the sample. But while the pXRF does not require destructive sampling of larger objects, they are not within a vacuum chamber, which is necessary for the detection of X-rays from lower atomic number (Z) elements that otherwise are absorbed in air. This is partly resolved when a vacuum is created within the pXRF (using a portable generator connected by a small tube) and the sample is flat, so that there is no air space in between the sample and the instrument window. The precision of measurements on elements such as Mg, Al, Si, and P, however, is not nearly as good as for higher Z elements, and elements below Na are not detectable at all. The other major difference with pXRF is its detection limits, as much as an order of magnitude less than for ED-XRF, and therefore providing fewer trace elements that may be used in archaeological sourcing studies. For the pXRF, filters have been designed for different materials to reduce the

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Figure 1 Non-destructive analysis of an ancient gold object from Colombia in the Orlando Museum of Art. Photo taken by R. H. Tykot.

background signal and maximize detection limits and precision.

Many archaeological materials may be heterogeneous, whether naturally (e.g., lithics), as a result of their production (e.g., ceramics), or due to degradation and contamination (e.g., metals). Pottery may be a combination of clay and temper, as well as having slip or paint on the surface, and copper-based metals may have pooling of lead and other elements, as well as corrosion on the surface. Care must be taken with what spots are chosen for analysis; recently broken (or freshly cut) edges of pottery may be better than the inner or outer surfaces. Using a pXRF, however, always allows multiple spot analyses so that trends and directions of surface contamination may be observed and incorporated into selection of additional analyses and interpretation of results.

Separate from issues of heterogeneity in archaeological samples is the precision of the pXRF. One study involved 25 separate analyses

on the same spot, for five different pottery sherds, as well as analysis of multiple spots on each sherd. This study showed that the precision was similar to regular XRF instruments—much better than the actual variation within the ceramics—and only a tiny fraction of the differences observed between ceramic source groups.

Multiple brands and models of pXRF instruments are available, with the same basic analytical principles, but different features and amenities. These include the sensitivity of the detector, and therefore the analytical time necessary; the size of the beam, and thus the area being analyzed; and the ability to adjust settings of voltage, amperage, and filter types to maximize results for different materials. In the examples presented here, two different pXRF models were used, with different filters when analyzing major elements in metals, or trace elements in lithics and ceramics. For major elements the analysis time selected ranged from 30–60 seconds, while for trace elements from 120–300 seconds. For many obsidian

artifact studies, an even shorter time is possible given the known variance between possible sources in particular regions, allowing analyses of more than 200 artifacts in just one day.

Archaeological applications

Obsidian

Given the homogeneity of obsidian, and insignificant changes between raw material and artifact, it is perhaps the most appropriate and easiest material to analyze by pXRF, with many studies published around the world. More than 7,000 obsidian artifacts from archaeological sites in the central Mediterranean have been analyzed to determine their geological source and to reconstruct trade. Following a detailed survey and collection of geological source samples on the Italian islands of Lipari, Palmarola, Pantelleria, and Sardinia, analyses by pXRF demonstrate that each may be distinguished from each other as well as from Melos in the Aegean and the Carpathian sources in the Balkans by just a few trace elements (Rb, Sr, Y, Zr, Nb).

The pXRF is even capable of distinguishing subsources for each island, with studies showing geographical and chronological differences in their relative usage. It is the attribution of obsidian artifacts to specific geological subsources that enables better understanding and interpretation of material selection, trade routes, and the socioeconomic systems in which they were embedded.

Ceramics

Ceramics may be heterogeneous due to how the clay is prepared and whether temper is added, while the surface may have slip, paint, or glaze, which may be an obstacle in doing non-destructive pXRF analysis. There are many potential clay sources that may have been used, with potential access to many points along rivers, and rarely a database with which to compare results on sherds. Instead, pottery “sources” are defined archaeologically with finds of production sites (e.g., kilns, wasters) and large assemblages of everyday wares. Using the pXRF allows analyses

of enough sherds to establish a local group, even if coming from multiple outcrops in the area and of different clay types, which may be further distinguished by analysis of more trace elements using INAA or ICP. Conducting such studies on multiple sites in a region provides information on possible locations of outliers from one site.

A number of ceramic studies using pXRF analyses have been published, several directly focused on the methodology and comparison with other analytical instruments, and others on particular research questions in many parts of the world. One was on prehistoric southeastern US ceramics, with multiple spot analyses of more than 500 ceramic artifacts from eight sites in northwest Florida. These included clay balls known as Poverty Point Objects from the Choctawhatchee Bay area, Tick Island in northeastern Florida, and the site of Poverty Point in Louisiana. Principal components analysis using Rb, Sr, Y, Zr, and Nb shows that several fall well outside the Apalachicola River group, and match with those from Poverty Point. These results support the hypothesis of small-scale, long-distance exchange between northern Florida and Louisiana.

Metals

The main use of elemental analysis on metal artifacts is for determining bulk element composition. The results for large numbers of copper-based as well as gold, silver, and lead objects may be used for assessing changes in production technology, access to tin and other metals, consistency in alloying different materials (e.g., tools, weapons, jewelry), and practices of recycling. Analyses also provide proper identification and description for museum exhibits and catalogues, and for many acquired museum collections, identifying some which are not authentic.

Conducting non-destructive analysis on the surface, however, raises potential problems due to degradation and/or contamination, as well as conservation practices that may have altered the composition. Analysis of multiple spots can quickly reveal significant variability in composition, which is not characteristic of a cast object, and perhaps a small area may be cleaned for reanalysis.

In the Orlando Museum, all but one of the “gold” objects are in fact tumbaga alloys, with high percentages of silver and copper (Figure 1). Other objects are labeled as “copper” or “metal”, with analyses revealing many as arsenical copper and just a few as bronze. One artifact, a knife, has too much Zn to be authentic. In the Tampa Museum, all objects were labelled as “bronze” or “silver”. An “Etruscan” object with Zn must be a fake since brass was not produced at that time. Four of the “silver” coins were mostly nickel, therefore also fake.

At the Roman site of Thamusida in Morocco, excavations revealed military equipment, including buckles, scabbards and horse harness fittings, and military diplomas. Dating to the early second to the third century CE, there were a great variety of copper-based alloys, with Sn and Zn in nearly all, many with Pb, and a surprising number with As and/or Ag. The compositions do not appear to be related to the social or functional purpose of the objects, but rather to the availability of raw and scrap materials.

Paintings

Analysis by pXRF of selected spots on painted surfaces produces results from varying depths based on thickness and composition, but cannot detect organic paints, and cannot distinguish colors based on their oxidation states. At the neolithic Genovese Cave on the island of Levanzo (Sicily), the pXRF was used to identify the kind of paint based on differences in element concentrations when compared with unpainted spots. The black figures had higher iron concentrations, sometimes also manganese, and others had the same composition as the adjacent unpainted rock surface, suggesting the use of charcoal. Red figures were always of iron (ochre), while white paint was high in calcium.

For later time periods, when many kinds of paints were used, just having elemental results may be limiting. Nevertheless, Cu peaks confirm what is thought for greenish colors, and gold-looking paint is usually pure gold. Red, however, may come from Fe-containing minerals or from the mercury (Hg) in cinnabar, as has been found in museums in Norway and in Sicily. Some Hg also was detected in non-red areas, suggesting

cinnabar was used in an earlier version now painted over. Tyrian red (or royal purple) is made from murex shellfish, and its use in paintings may be confirmed by a high bromine (Br) peak.

Bone

Measuring elemental concentrations in bone or teeth is well established for studying dietary practices (Ca, Sr, Ba) as well as potential consumption of poisons (Pb, As), and can complement isotopic analyses. The ratios Sr/Ca and Ba/Ca decrease with trophic level, so are especially indicative of the consumption of aquatic resources. While other studies are done on interior samples that are ashed, analysis by pXRF of a well-cleaned surface may also be successful. Bones from 67 individuals from four sites in Florida were analyzed. Those from the inland site of Belle Glade had the highest ratios; Miami One on the Atlantic coast had lower values; and Horr’s Island and Weeden Island on the Gulf coast had the lowest. The tight clustering of the Horr’s Island and Weeden Island individuals supports the premise that the results are reliable and not significantly altered by contamination and/or decay. The results are also consistent with greater and more regular accessibility of marine foods on the shallower Gulf side, as confirmed by stable carbon and nitrogen isotope analyses.

SEE ALSO: Elemental Analysis of Pottery; ICP-MS and Material Analysis; Neutron Activation Analysis (NAA); X-Ray Fluorescence Spectrometry (XRF)

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Radar

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This discussion of radio detection and ranging (RADAR) focuses on two categories that are most applicable to archaeological research: SYNTHETIC APERTURE RADAR and GROUND-PENETRATING RADAR. RADAR is an active remote-sensing (see AIRBORNE REMOTE SENSING) technique where pulses of a generated energy signal (a radio wave) are sent out through a transmitting antenna, and the direction and quantity of backscattered or reflected energy are recorded by a receiving antenna (Conyers 2013). Both SAR and GPR operate in the microwave portion of the electromagnetic (EM) spectrum. In GPR, the depth of ground penetration is linked to the physical size of the antenna and the oscillating frequency of the transmitted wave. In SAR, finer pixel resolution is achieved by approaching a target from multiple viewing angles and processing the composite backscattered signature. In both systems, portions of the radar energy reflect (backscatter) when they encounter changes in the physical and chemical properties of surface or subsurface materials. Varying the wave frequency and polarization (orientation of the electric field) of the EM wave during SAR flights will generate data across multiple bands, enabling increased target discrimination and characterization (Chapman and Blom 2013; Lasaponara and Masini 2013). Multiple GPR surveys over an area using offset grid orientations or different antenna frequencies can help characterize subsurface features (Conyers 2013).

SAR data provide an aerial or satellite view of archaeological landscapes or features using wavelengths ranging from meters to millimeters. Processing, calibrating, and geocoding the raw data result in an image where each pixel depicts the reflectivity of a portion of the ground (Chapman and Blom 2013). Unlike optical imagery, SAR is less susceptible to changes in

atmospheric conditions (e.g., increased cloud cover), can produce imagery during the day or night, and is useful in characterizing surface features or microrelief in forested environments (Lasaponara and Masini 2013). SAR's ability to penetrate the ground is strongly influenced by surface characteristics and by the soil's moisture content. Early uses of SAR in the 1980s had unexpected benefits for archaeology when NASA researchers flew over the Sahara and identified buried paleochannels below the sand (Lasaponara and Masini 2013). Airborne SAR (AIRSAR) conducted over Angkor Wat in Cambodia is one of the most notable uses of this technology in archaeology (Moore, Freeman, and Hensley 2007). Since the 1990s, SAR data aided in the identification of undocumented temples and an extensive water management system, and expanded the known settlement boundaries of Angkor Wat's well-integrated urban system. While archaeological applications of SAR are often geared toward settlement detection and the mapping of architectural features, the range of uses is increasing (e.g., to study Maya settlement (Garrison et al. 2011), irrigation structure, and wetland ecology (Adams, Brown, and Patrick 1981)). A notable area of recent research is in monitoring looting and structural deformation using time series collections. Today, many archaeological maps, landscape-scale geospatial analyses, and feature identification in remote regions utilize digital elevation models (DEMs) derived from shuttle radar topography mission (SRTM) data, which was collected in 2000 using interferometric SAR (InSAR). SRTM 90 m resolution DEMs provide nearly worldwide coverage and are freely available from NASA's Jet Propulsion Laboratory. Increasingly advanced technology and processing procedures will continue to expand the applicability of SAR to archaeological practice (see SAR (see SYNTHETIC APERTURE RADAR) for a more thorough discussion).

While not all surveys are successful at identifying features of archaeological interest, GPR is more common in archaeological practice than SAR. GPR has been utilized in archaeology since the 1970s, but its application has increased since

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the turn of this century as the quality of the instruments and processing software improved. As radar waves encounter interfaces between materials with different dielectric properties, portions of the wave are reflected back to the surface antennae (Conyers 2013). The amplitude of the reflected wavelet is determined by the magnitude of difference in the properties of the two materials and the frequency of the antenna used. Mid-range frequency antennas (~400–500 MHz) are often suitable for archaeological studies. Higher-frequency antennas (~800–900 MHz) can provide higher-resolution data but at shallower depths; lower-frequency antennas (~100–200 MHz) are useful for identifying substrata or features in soils with a tendency to attenuate the wave's energy. All received energy from a single transect is plotted in two dimensions to form a radargram, which illustrates each received wavelet plotted by its relative amplitude and position in two-way travel time (Goodman and Piro 2013). Each transect's radargram is stacked sequentially into a 3D block of data and then sliced horizontally into "time slices" (the plan view at depth) in nanoseconds. Both the radargrams and time slices are important for analyzing and interpreting GPR data (Conyers 2012).

For many years, archaeologists considered dry sandy environments to be the best in which to conduct GPR surveys, particularly for resolving stone architecture. However, improvements in GPR technology and software, and in how one interprets archaeological features within GPR data, have resulted in more experimentation and innovative processing techniques. The amount of publications on archaeological case studies since the beginning of this century underscores how successfully GPR is being applied across diverse environments and soil conditions around the world. Conyers (2012) provides many examples and summarizations of GPR use and interpretation across archaeological contexts, including the identification of pithouse floors and perishable architecture, irrigation ditches and agricultural fields, burial trenches and unmarked graves, features and built surfaces within monumental earthen architecture, and a variety of stone architecture and urban environments. GPR has also been successfully used to identify and map

historical features, including building foundations and cellars, trash middens, wooden coffins, and, occasionally, mass graves and historical campsites. It is also useful for geoarchaeological studies, including mapping complex stratigraphy and identifying buried surfaces. Understanding the soil types present and ground conditions, such as the amount of recent saturation or types of mineral inclusions, is important for increasing the success of a GPR survey. See GPR (see GROUND-PENETRATING RADAR) for a more thorough discussion of its use in archaeological survey.

SEE ALSO: Airborne Laser Scanning and Lidar

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Sampling in Airborne Field

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The “view from above” was first obtained in antiquity from elevated points, and later using balloons followed by kites, airplanes, rockets, and finally satellites. Historically, aerial photography was the first remote sensing tool extensively used for digital archaeology. The first aerial archaeological surveys were made on Rome in 1900 and on Stonehenge in 1906 by using balloons. Aerial photography dramatically improved before and during the world wars. In the first three decades of the twentieth century, pioneering aerial archaeological surveys were conducted in England and Sudan by O. G. S. Crawford, and in Syria by A. Poidebard.

For most of the twentieth century, aerial photography was the unique remote sensing tool for surveying emerging archaeological remains, as well as for detecting underground archaeological structures through the reconnaissance and interpretation of proxy indicators, such as crop-, damp-, soil-, and shadow-marks (Figure 1), which are the results of the physical and topographical interaction between buried archaeological deposits, soil and vegetation cover (Crawford 1929).

In particular, crop-marks are linked to the presence of buried walls and/or filled ditches in vegetated areas. They produce local variations in moisture and nutrient content and, consequently, in the growth of vegetation, which can be revealed by differences in height or color of crops.

Soil-marks are differences in soil color, which are particularly visible after ploughing as it brings to light dry material related to buried walls, or wet material related to pits and moats.

Damp-marks occur when the presence of archaeological deposits induce local changes in

the drainage capability of the soil and can be revealed by changes in color or texture.

Shadow-marks are produced by micro-topographic relief which is the residue of eroded shallow remains and earthworks, viewable from above when the sun is low in the sky.

Less frequent proxy indicators are snow-marks that occur as soil-marks mainly due to differences in bulk density, which determines the water balance and thermal behavior, and in turn impacts the presence of snow over archaeological deposits.

Today, multispectral images of archaeological marks can be produced thanks to spectral variations in specific channels or spectral indices.

The visibility of the above-mentioned proxy indicators has great intra- and inter-year variability due to changes in crop types and phenology, soil moisture content and other surface parameters. Additionally, the visibility of micro-relief depends on many factors, such as off-nadir viewing angle of the collected imagery, time of image acquisition, view geometry, sun angle (micro-topographic relief variations are more visible in early morning or late evening), and surface characteristics; in particular, the presence of vegetation can completely cover any micro-relief. These limitations can be overcome by an airborne laser scanner (ALS), also referred to as “light detection and ranging” (lidar).

Lidar is a quite recent (mid-1990s) remote-sensing technique used to measure terrain elevation and also to carry out a variety of new, promising applications including archaeology. Currently, a lidar survey could be carried out by using two different types of sensor systems: conventional or discrete echo scanners, and full-waveform ones. The first, generally, deliver only the first and last echo, thus losing many other reflections. The second are able to detect the entire echo waveform for each emitted laser beam, thus offering improved capabilities, especially in areas with complex morphology and/or dense vegetation cover.

Nowadays lidar is regarded as a well-established tool used for archaeological and cultural landscapes. The majority of published studies are

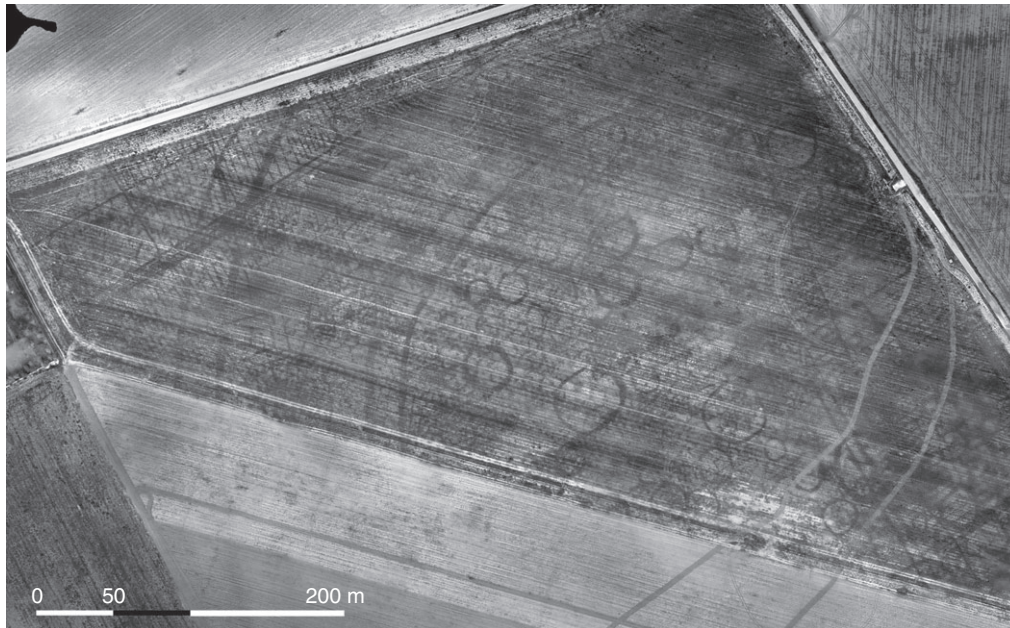


Figure 1 Aerial photograph of soil- and crop-marks related to a Neolithic settlement near Lucera, Italy. © CNR-IBAM/IMAA.

based on data collected by conventional ALS, for the management of archaeological monuments, landscape studies, and archaeological investigations, to depict micro-topographic earthworks in bare ground sites and in forested areas. Actually, the great potential of lidar in archaeology is mainly linked to its unique capability to penetrate vegetation canopies and identify archaeological earthworks and remains even under dense vegetation.

The recent discoveries of Arlen Chase in Belize (Chase et al. 2012) and Damian Evans in Angkor (Cambodia), the investigation of abandoned medieval villages in central and southern Italy by Rosa Lasaponara and Nicola Masini (see Figure 2; Lasaponara and Masini 2009), and the prospection of ancient landscapes in Austria by Michael Doneus et al. (2012) demonstrate the effectiveness of this technology for archaeological research in wooded areas.

The interpretation of lidar results to identify potential traces of cultural interest is based on shape, pattern, texture, and shadow. To this aim, it is crucial to process the point clouds and classify terrain and off-terrain objects by applying adequate filtering methods, in order to obtain a

very accurate digital terrain model (DTM) and to use appropriate visualization techniques (Hesse 2010) of digital models aimed at emphasizing changes in morphology and discontinuities in the landscape, and any kind of earthwork attributable to human activity.

Recently lidar has also been used for underwater archaeology with promising results, as in the case of a Roman harbor in Croatia by Doneus et al. (2012).

A valuable alternative to traditional aerial photogrammetry and lidar for operative use in archaeology is offered by the use of unmanned aerial vehicles (UAVs), which have several advantages, particularly low cost and the ability to cover large areas in a short time. Moreover, UAVs provide innovative vision and allow us to obtain very high-resolution products (orthophoto, digital elevation models) by using easy tools of image processing based on structure-from-motion (SfM) (Nex and Remondino 2014).

SfM is a range imaging technique that allows the estimation of three-dimensional objects from image sequences which may be coupled with local motion signals. Compared with conventional photogrammetry, which requires a single

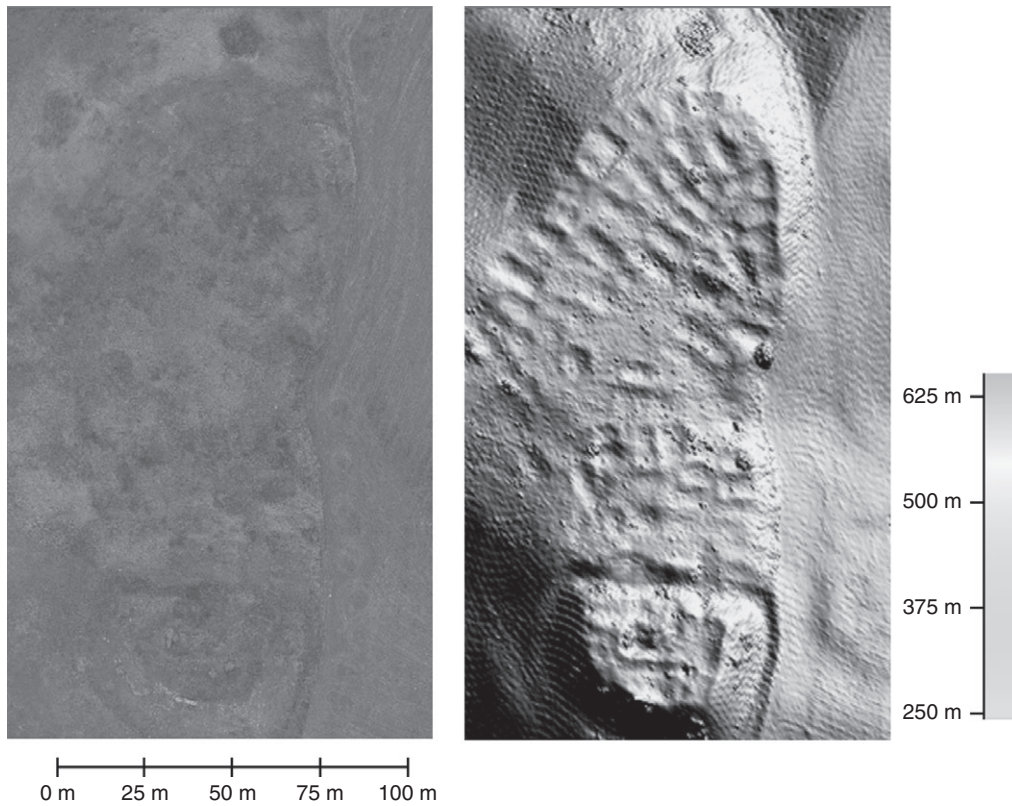


Figure 2 Orthophoto and digital terrain model of the abandoned medieval village of Irsi (near Matera, southern Italy). © CNR-IBAM/IMAA.

stereo-pair, SfM needs multiple, overlapping photographs as input to feature extraction and 3D reconstruction algorithms. The usefulness of UAV-based investigation has increased, thanks to the capacity to integrate it other methods of remote sensing including geophysics, optical and synthetic aperture radar (SAR) remote sensing.

Additional remote-sensing technologies for sampling in the airborne field exploit sensors such as thermographic, ultraviolet, hyperspectral, and SAR, which provide information by exploiting regions of the electromagnetic spectrum invisible to the human eye (outside the range of 400–750 nm that is used in normal photography).

In particular, the capability of thermographic imaging to detect subsurface archaeological features is due to their contrast in thermal inertia with respect to their background, which depends on their composition, density, and

moisture content (Cassana et al. 2014). Aerial thermography proved to be an effective tool for the identification of pits, ditches, field boundaries, and shallow remains.

Hyperspectral sensors tend to enhance the contrast between archaeological deposits and their surroundings, exploiting those spectral bands more sensitive to moisture content and soil types.

Near-ultraviolet sensors generally acquire images at wavelengths ranging from 315–400 nm, and at low-altitude flight can detect features linked to soil- and damp-marks. Recently the use of SAR data in archaeology has shown the great potential of these technologies for site detection (buried or emerging archaeological remains) and monitoring, as well as for landscape archaeology.

Airborne SAR can overcome some limitations of optical imaging, providing the unique capability to “penetrate” into the soil (and to some

extent also the vegetation) especially in desert areas, providing a detailed map of subsurface structures and the paleoenvironment.

SEE ALSO: Aerial Photography; Airborne Laser Scanning and Lidar; Archaeological Photography; Digital Photogrammetry; IR Thermography; Lidar Data Visualization and Processing; Satellite Hyperspectral and Multispectral Imaging; Synthetic Aperture Radar

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FURTHER READINGS

Sampling in Marine Field

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Sampling in marine field is beneficial in extracting a representative subset of information from an archaeological site. Complete archaeological excavations can be costly in marine and terrestrial settings, and are often unnecessary. Archaeologists commonly leave part of a site intact for future analysis as new, unforeseen technologies, and sampling strategies are devised. A well-formulated sampling strategy using an appropriate analytical technique can yield both cultural and environmental data to reconstruct the past.

The sampling of deposits in a marine setting within archaeology has advanced analytically by adapting methods from anthropology, biology, chemistry, ecology, environmental studies, geography, geology, and remote sensing. Due to the many lines of evidence required to interpret the past, sampling in a marine field is a collaborative endeavor. As a result of this integration of cultural and environmental information, complex questions regarding human–environment interaction can be addressed (see PALEOENVIRONMENTAL RECONSTRUCTION) (Johnson and Stright 1992). Archaeological investigations in coastal and marine environments reveal sampling advancements for inundated sites and the growing field of submerged archaeology on continental shelves throughout the world, including the Gulf of Mexico (Faught 2004; Masters and Flemming 1983).

Traditional terrestrial methods, such as shovel testing and small excavation units (see TERRESTRIAL EXCAVATION), have been successful in marine sampling, particularly in an inundated marine setting where the excavator can stand upright to complete the excavations, on sites with restricted access to diving gear, or in remote areas. Offshore shovel tests can clarify the extent of a site that has been impacted by sea-level rise where the majority of the site is presently underwater. The

underwater archaeological equivalent to shovel tests are cores (see CORING) and induction dredging. These sample the seafloor at known archaeological sites. Cores are useful in extracting environmental data, whereas dredging is the preferred method for extracting cultural information.

Sediment samples collected from shovel tests, excavation units, cores, and dredging yield cultural and environmental data for reconstructing and evaluating ancient landscapes. Typically, sediment samples are extracted from cores or from the walls of excavation units (see SAMPLING IN ENVIRONMENTAL STUDIES). These extracted samples are analyzed using sedimentology. Particle size analysis is used to determine the amount of sand, silt, and clay. The differences in particle size distributions of sediment can aid in reconstructing relict rivers, levees, and other landforms (Johnson and Stright 1992). Loss-on-ignition, magnetic susceptibility (see MAGNETIC SUSCEPTIBILITY), and macroscopic examination of sediment from underwater excavations are additional types of sediment analysis. Loss-on-ignition measures the percent of organic material in sediments and is particularly useful for organic-rich sediments, such as in areas with peat deposits, to determine the rate of sea-level rise (see SEA-LEVEL CHANGE). Magnetic susceptibility can determine whether areas have been magnetized, usually from the heat from fires. Macroscopic analysis of sediment is where vegetation that is preserved in the sediment is identified through a microscope. This method is most useful in organic environments where there is visible plant structure. Increasingly, pollen analysis (see DATING POLLEN and PALYNOLOGY) is used to date as well as reconstruct environments. Additionally, microfossils including diatoms (see DIATOMS), foraminifera, and ostracods (see OSTRACODS AND CLADOCERANS) are analyzed because they are sensitive indicators of sea-level fluctuations.

Sediment chemical analysis using inductively coupled plasma mass spectroscopy (see ICP-MS AND MATERIAL ANALYSIS) can be adapted from terrestrial archaeology for a marine setting. The analysis of the spatial variation of concentrations

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of elements is well established in determining activity areas on terrestrial archaeological sites. The sampling of marine sediment from the seafloor of an archaeological site can identify activity areas not apparent in the archaeological record, such as areas for food preparation and disposal, hearths, the remains of meals, and ash from fires.

The list of sampling methods discussed above for a marine field is not exhaustive. All of the methods mentioned have been developed to study intertidal, near-shore, and offshore deposits, which indicates the versatility of these methods as they are applied at various scales.

SEE ALSO: Chemistry in Archaeology; Geoarchaeology; Geomorphological Survey; Marine Excavation; Soil Chemistry in Archaeology

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Satellite Hyperspectral and Multispectral Imaging

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What's in a name?

Satellite imaging is a part of remote sensing (see AIRBORNE REMOTE SENSING), which can be broadly defined as the collection of data about a scene or object without having direct physical contact with it. In archaeology, remote sensing is a general name given to all techniques that use propagated signals to observe the Earth's surface from above. Based on their specific characteristics, remote sensing techniques can be classified in different ways: imaging versus nonimaging, passive versus active, optical versus nonoptical, airborne versus spaceborne. Whereas passive remote sensing systems capture naturally occurring radiation, active systems produce their own radiation. Airborne systems operate from within the Earth's atmosphere, while spaceborne systems deploy a sensor mounted onboard a spacecraft (often a satellite) that orbits the Earth. When dealing with an imaging system, the output is an image, whereas nonimaging systems can deliver sounding data or emission spectra.

Although exceptions exist, archaeological satellite multi- and hyperspectral imaging generally refers to the amalgam of passive remote sensing techniques that capture a specific part of the Earth's reflected solar energy or self-emitted thermal energy from space, and turn that into a (digital) image. In addition, these spaceborne imagers only operate in the optical electromagnetic spectrum, which conventionally incorporates the complete ultraviolet to infrared bandwidth, comprising radiation with wavelengths between 10 nm (0.01 μm) to 1 mm (1000 μm). However, remotely-sensed imaging in the optical range usually begins at the

visible waveband (i.e., 400–700 nm). Together with the near-infrared (NIR; 700–1100 nm) and short wavelength infrared (SWIR; 1.1–3 μm), this waveband is known as the solar-reflective spectral range because imagery is predominantly generated by reflected solar energy. The neighboring mid-wavelength infrared (MWIR; 3–6 μm) range is considered an optical transition zone, as the solar-reflective behavior slowly shifts in favor of self-emitted thermal radiation. In both the long wavelength infrared (LWIR; 6–15 μm) and far/extreme-infrared (FIR; 15 μm to 1 mm), the imaging process is almost uniquely governed by the thermal electromagnetic radiation emitted by the scene objects themselves. As a result, the MWIR to FIR optical region is commonly denoted the thermal region. Finally, “multi-” and “hyperspectral” refers to the fact that different spectral bands/channels capture the reflected or thermal energy.

Spectral imaging (which is a term that covers both multi- and hyperspectral imaging) starts as soon as optical electromagnetic radiation is detected and digitized in four spectral bands (see MULTISPECTRAL AND HYPERSPECTRAL IMAGING). The amount of captured bands is also one of the distinguishing factors that denotes a spectral imaging system as “multi” or “hyper”. A multispectral device digitizes the reflected (and/or emitted) electromagnetic radiation in around 4–10 adjacent spectral bands that are about 100 nm wide and often feature a small spectral gap in between them (e.g., 730–850 nm, or 1050–1200 nm). Hyperspectral imaging extends this multispectral concept by capturing spectral data in at least 10 (nearly) contiguous (i.e., adjacent and not overlapping) narrow spectral channels.

Sensor characteristics and their influence

Not all spaceborne images are created equally, and as such, not all have the same archaeological potential. This becomes clear when one understands that digital image pixels always

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represent averages in time, space, and spectral range. The integration time or shutter speed of the imager determines the sampling of the time dimension. The two other sampled dimensions define important image characteristics known as spatial resolution and spectral resolution, respectively defining the minimum distance between distinguishable objects and the spectral details that can be resolved in the image.

Although the final spatial resolution of an image depends on many factors, one of the key factors is the so-called ground sampling distance (GSD). Most imaging sensors consist of individual photosensitive elements or photosites. The distance between a photosite's center and the center of the neighboring photosite is denoted the "detector pitch". The GSD is the corresponding distance projected onto the Earth's surface, stating the horizontally or vertically measured scene distance between two consecutive sample locations (even though the term is technically wrong, pixel size is often used as a synonym for GSD). Amongst other factors, the GSD is determined by the scene's local topography, the viewing direction of the camera (nadir or off-nadir), the focal length of the lens, and the distance of the camera to the scene. In general, spaceborne images are acquired by platforms in orbits between approximately 160 km and 2000 km above the surface of the Earth. A satellite operating in a lower orbit will therefore be capable of generating a smaller GSD.

Concerning satellite imagery, the so-called panchromatic image always features the highest spatial resolution. This is a greyscale image created by one spectral band that is sensitive to more or less all ("pan") wavelengths (or colors, hence "chroma") of visible electromagnetic energy. Virtually every passive spaceborne imager creates a panchromatic image. The spectral resolving power of such a panchromatic band as well as any spectral channel is measured by the full width at half maximum (FWHM). The FWHM of a band quantifies its spectral bandwidth at 50% of its peak responsivity. For example, hyperspectral bands often have a FWHM of circa 15 nm, while multispectral sensors capture energy in bands with 100 nm FWHM. To sufficiently resolve small spectral features, the spectral bands should have a width smaller than or comparable to the spectral

details in the signal and be placed in the correct part of the spectrum. Since the total amount of incoming radiant energy is related to a band's FWHM, the photosites that generate spaceborne multispectral images are commonly 4–16 times larger compared with the spectrally-wide panchromatic band (350–400 nm FWHM). Due to the square nature of most photosites, this translates to a GSD that is two to four times lower for multispectral images compared with their panchromatic counterpart.

Although most optical spaceborne imaging systems are multispectral, hyperspectral imagers do also exist. Due to their higher spectral resolving power (i.e., smaller FWHM for every band), hyperspectral imagers sample over an even larger spatial extent to obtain the necessary incoming electromagnetic energy to produce a decently exposed image. As a result, spaceborne hyperspectral imagers will always feature a coarser spatial resolving power than their multispectral counterparts. To overcome this physical tradeoff between spectral and spatial resolution, spectral data are often fused with panchromatic spatial details in a procedure called pansharpening. In the SWIR wavelength range and beyond, the amount of reflected or self-emitted energy is so low that imagers have to increase their spectral bandwidth and/or their detector pitch to acquire enough energy.

Digitally capturing a scene also means that the sampled analogue signal needs to be quantized to discrete data numbers. The bit depth of this quantization determines the achievable tonal range of the image, thereby providing images with a radiometric resolution. Although the temporal sampling is determined by the integration time during image acquisition, the temporal resolving power of a remote sensing imaging system generally refers to the repeat period or the capability to view the same scene at regular intervals.

Archaeological use

Spaceborne imagery used for archaeological practice comes from either non-military or declassified military sensors. Due to their often surprisingly high spatial resolution (Fowler 2010), the latter category is an essential resource for all

studies that focus on the change and monitoring of the landscape or in a general supporting role to produce base maps (certainly in those areas lacking conventional aerial footage). However, this imagery cannot be categorized as multi- or hyperspectral since it generally comprises only one panchromatic band. In addition, these images are also spatially, spectrally, and radiometrically outclassed by many present-day civilian products (Scardozzi 2016). Although aerial footage still has the edge in terms of spatial resolution, the steady technological leaps of spaceborne imagers has resulted in, by 2017, GSDs of the order of 40 cm.

It is the combination of this improved GSD, the inherent synoptic perspective (i.e., footage with a very large spatial coverage), and the spectral capabilities which, together with the improved (online) access, provides many interesting opportunities for landscape archaeologists when compared with conventional aerial imagery. Besides, satellites can image areas that have limited or no access due to airspace restrictions or bureaucratic red tape. As a result, many present-day spectral products are used for archaeological prospection. Since buried archaeological residues can change the chemical and physical properties of the local soil matrix, their presence might be disclosed by growing- or ripening-induced differences in the reflectance or height of vegetation on top of the remains (i.e., vegetation marks), or distinct tonal differences in the ploughed soil (soil-marks). Dedicated spaceborne imaging devices enable the comprehensive mapping of such plough-levelled sites through these proxies of soil- and crop-marking. Examining the remotely sensed imagery for such pertinent archaeological information can help to develop knowledge about people in the past. Here, the fundamental difference of multi- versus hyperspectral imagery again plays an important role. Obviously, more and narrower spectral bands have a greater potential for detecting subtle spectral reflectance differences in the soil and vegetation cover. On the other hand, hyperspectral images suffer from spatial resolution constraints that have a lesser effect upon multispectral products. For example, the hyperspectral imager CHRIS onboard the European Space Agency's 2001-launched Proba-1 satellite acquires 19 programmable spectral bands in the 415–1050 nm range. However, its 17 m GSD only renders the

imagery useful for mapping very broad landscape features such as paleochannels, road complexes, or ancient water management structures. Even though many civilian spaceborne hyperspectral imagers with improved spatial resolving power have been announced in the past years, none are currently operational.

Although the wider bandwidth of the multispectral products might average subtle spectral details away, the fact that data are generally recorded at well-placed spectral positions in the NIR and SWIR still makes them very suitable for visualization of reflectance differences between diverse soils and health states of vegetation. For instance, the imaging sensors onboard DigitalGlobe's commercial WorldView-3 satellite provide panchromatic imagery with 0.31 m GSD and eight multispectral bands in the 400–1040 nm range. The latter feature a GSD at a nadir of 1.24 m and even comprise special yellow (585–625 nm) and red edge bands (705–745 nm) for vegetation mapping. Additionally, WorldView-3 also provides another eight multispectral bands at 3.7 m GSD in the SWIR region (1195–2365 nm). When pansharpened, any of these spectral images can be very appropriate for identifying archaeological features, mapping landscape structures, assessing spatial relationships between sites and their environment, as well as identifying and monitoring threats (such as looting). However, when one needs to spatially resolve the soil and crop marks that result from very small features (such as pits and postholes), an airborne vantage point (see AERIAL PHOTOGRAPHY) still remains superior. They do, however, generally lack the synoptic perspective of spaceborne footage. Even for decade(s)-old spaceborne spectral imagery featuring GSDs of at least a few meters, this landscape-centered perspective remains a major advantage in archaeological practice.

In the future, the regular data acquisition by these spaceborne instruments and the ever-improving spectral and spatial quality of newly launched imagers will only continue the growth of multi- and hyperspectral satellite imagery as a primary archaeological data source. Together with a possible decrease in purchasing costs and the ongoing advances in image processing techniques, they will continue to deliver increasingly useful tools for archaeologists to exploit.

SEE ALSO: Aerial Photography; Airborne Remote Sensing; Desert Environments; Digital Cartography; Digital Photogrammetry; Environmental Archaeology; Environment and Landscape; Geoarchaeology; Heritage and Landscapes; Imaging; Infrared Reflectance Spectroscopy; IR Thermography; Multispectral and Hyperspectral Imaging; Multispectral and Hyperspectral Imaging of Artworks; Photogrammetry and Stereophotogrammetry; Reflectometry; Synthetic Aperture Radar; Thermography; Vegetation Modeling Using Pollen Data

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FURTHER READINGS

Soil Penetrometry

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Penetrometry concerns the attributes and behaviors of surface and subsurface soils. At its most basic, penetrometry is the measurement of soil resistance for the purpose of assessing soil compaction. In general, the extent to which soil is compacted has relevance to an array of earth sciences, including geomorphology, sedimentology, pedology, and glaciology. Soil compaction is also of interest to the fields of geoscience that are more directly concerned with the qualities of soil as they affect or are affected by human behavior, including edaphology, agronomy, and engineering geology. In archaeology, researchers have been particularly attentive to the ways that variable soil compaction provides insights into the agricultural potential and use of ancient landscapes, as well as the activities that create and transform cultural features, such as house floors, ancient roads, and cemetery grave plots.

Penetrometers are the instruments employed in soil penetrometry and come in several forms, with some notable differences in portability, precision, measurement, and cost (Figure 1). The simplest of penetrometers are manually operated and measure how much force a soil is able to withstand before giving way to a penetrating rod. Sometimes also marketed as “soil compaction testers,” these instruments are typically the least expensive and most portable, although they are also less precise and capable of only simple characterizations of soil behavior.

The pocket penetrometer, for example, weighs no more than 150 grams and can easily be transported and used for frequent on-site measurement of soil compaction. Operation requires minimal training: holding the instrument with only one hand, the user grips the cylinder and places the tip of the piston on the surface of the soil to be measured. Pushing downward at a right angle compresses a calibrated stainless steel

spring, forcing an indicating ring to slide up the piston. At the point that a piston calibration mark sinks to the same level as the soil surface, the user stops exerting downward pressure and records the measure as indicated by the new location of the indicating ring against a piston-mounted scale (see Figure 1). Given the simple design of the instrument, readings are best regarded as approximations of actual soil resistance, although manufacturers suggest that accuracy to 0.122 kg/cm² (1.74 PSI or 0.125 tons/ft²) is possible. For weak soils and sediments (e.g., uncompressed beach sand), an adapter can be attached to the end of the piston.

Dial penetrometers are larger than their pocket counterparts, although they are similarly operated by manually applying downward pressure to measure soil resistance as a proxy for soil compaction. An important distinction is that dial penetrometers are capable of measuring soil compaction at known depths below the surface. The instrument's t-shape handle features a dial gauge that displays soil resistance as measured in PSI by a cone tip at the end of a 60-cm stainless steel rod. Softer soils often require a larger tip, whereas harder soils can be assessed with a smaller cone. Most dial penetrometers, however, are capable only of measuring resistance to an accuracy of 50 PSI (3.52 kg/cm²).

More complex instruments used for penetrometry, such as cone penetrometers, are considerably larger and require mounting to wheeled or tracked vehicles (e.g., a truck, tractor, or trailer), usually equipped with hydraulic leveling and land anchors so as to compensate for the reaction of hydraulically driving a testing probe into the ground. In cone penetrometer testing (CPT), ease of instrument portability is sacrificed for greater reliability of measurements. For example, the use of a hydraulic piston to drive the instrument's cone-tipped rod downward eliminates variability in the rate at which force is exerted on manually operated instruments, like dial and pocket penetrometers. While the cone measures penetration resistance (q_c), the probe rods on many CPT instruments are also equipped

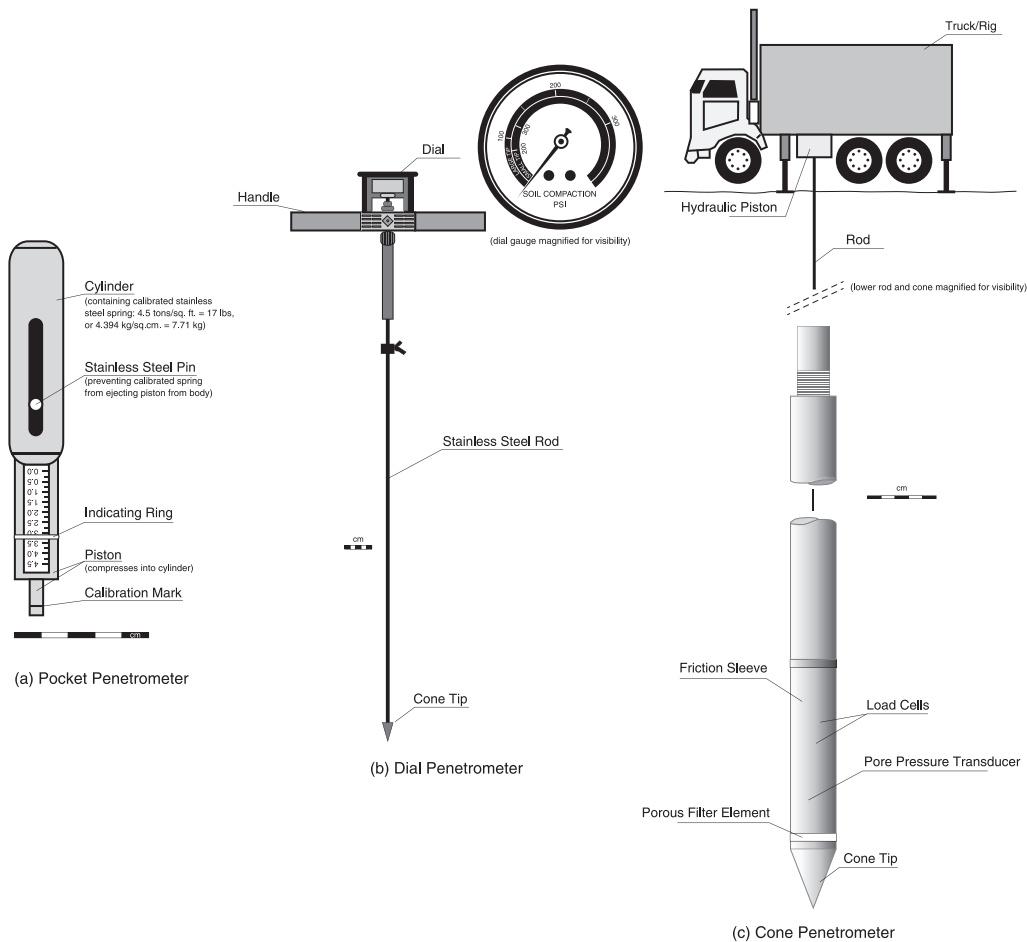


Figure 1 Three types of penetrometers available to archaeologists: (a) pocket penetrometer; (b) dial penetrometer; and (c) cone penetrometer.

with friction sleeves that measure lateral friction resistance (f_s) as the probe extends downward. The relationship of side friction to tip resistance (R_p) can be used to construct soil behavior profiles, although this classification should not be confused with analysis of grain size distribution as determined by the Unified Soil Classification System (USCS) (Robertson and Cabal 2015).

Additional sensors can be added to the cone used in CPT, thus greatly expanding the kinds of data collected and affording fuller characterizations of subsurface soils. Piezocone penetrometer testing (CPT-U), for example, employs a cone equipped with porous elements that measure soil pore pressure (u). Other sensors afford conductivity measurements (CPT-C) as well

as seismic shear wave and compression wave velocity measurements (CPT-S).

Although penetrometers have been around since the 1950s (Mathieu and Toogood 1958), implementations of penetrometry in archaeological inquiry were rare prior to the 1990s. Since, a modest corpus of research has emerged, and the analytical potential of penetrometry is evident in a wide array of questions and types of field investigations to which penetrometry methods have already been applied. For example, CPT data have been shown to be both reliable and accurate for determining soil stratigraphy and topographic features of buried landscapes in Belgium (Missiaen et al. 2015). Although CPT methods do not yield insights that fully

substitute for those derived from conventional coring methods, they are highly complementary and may allow for even more efficient sampling strategies when profiling subsurface sediments. Elsewhere, penetrometers have been used to assess and map variable compaction of soils for the purpose of locating surface and subsurface cultural features. Some examples include the use of pocket penetrometers to search for cart paths connecting eighteenth century plantations in rural Delaware (Burrow et al. 2014), and the use of dial penetrometers to reveal the locations and delimitations of burial plots in Colonial settler cemeteries (Trinkley 1999).

Penetrometry has also been successfully incorporated into the basic suite of data recovery methods applied during formal excavation. In the Pacific Northwest, pocket penetrometers have proven useful for quantifying otherwise subjective assessments of variable strata compaction during the investigation of ancient house features. Indeed, compaction data gathered with penetrometers have aided in the task of identifying house floors in noncontiguous excavation units, and for the purpose of collecting context-sensitive sediment samples for macrobotanical and microartifact analyses (Graesch, Shankel, and Schaepe 2015).

Penetrometry has also played a role in the study of recent site formation processes that adversely impact cultural resources. CPT data, for example, have been used to assess changes in the compaction of sediments after heavy machinery is operated on the surfaces of archaeological sites (Ardito 1994). Elsewhere, penetrometers have been incorporated in experiments concerning the effects of farm equipment on fragmentation rates of pottery and bone artifacts (Dain-Owens et al. 2013), as well as taphonomic research addressing the impact of armadillo burrowing in archaeological deposits (Araujo and Marcelino 2003).

In all of these cases, archaeologists have used penetrometers that were designed to meet the needs of geotechnical applications, particularly those based in agronomy and engineering geology. Given recent demonstrations of the relevance of penetrometry to archaeological inquiry, it is reasonable to expect that further developments in penetrometer technology may be driven by the specific needs of archaeologists. Archaeologists are already working to develop instruments that

have the portability of manual penetrometers but the sensory complexity and accuracy of CPT instrumentation (Russo 2015). Such penetrometers could greatly improve the task of detecting buried cultural deposits in places inaccessible by vehicles.

SEE ALSO: Coring; Formation Processes; Soil Survey

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Soil Phosphate Chemistry

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Lack of artifacts in archaeological settings

Many archaeological sites were slowly abandoned and artifacts were moved or taken from their locus of use either in ancient or modern times. Archaeological interpretation is difficult when artifacts are displaced or altogether missing. In the humid tropics, in particular, high decomposition rates result in the complete loss of perishable artifacts, particularly those related to food products. Analysis of ancient human activities at archaeological sites can be facilitated by determination of certain elemental residues that persist in the soils and floors. Chemical residues of ancient activities represent invisible yet critical artifacts of ancient human lives.

Phosphorus concentrations in soils and floors

Examination of soil chemical concentrations can elucidate areas where past activities repeated in a given locale would have left elevated concentrations associated with byproducts of such activities. Increased levels of phosphorus (P) is one of the most archaeologically significant anthropogenic alterations of soils (Holliday 2004). Phosphorus is a structural component of phospholipids, nucleic acids, and many other biological molecules within living tissues. Anthropogenic P originates from plant and animal materials gathered for food and brought to settlements for consumption. As food, animal, and human wastes are disposed, the organic P constituents decompose and inorganic phosphate ions are released, only to become readily fixed

or adsorbed on the surfaces of soil particles at the site of accumulation (Barba and Ortiz 1992; Terry et al. 2000). These fixed forms of phosphate are highly insoluble and resistant to physical and chemical processes of leaching, oxidation, and reduction. Fixed P remains stable in soil and most occupation surfaces for centuries (Holliday 2004; Parnell, Terry, and Golden 2001). As humans concentrate organic matter in specific locations and residues from the organic matter are worked into the soil, inorganic P concentrations can increase significantly compared with the original P concentrations of occupation surfaces. Therefore, elevated P levels in soils in comparison to background concentrations are predictors of ancient food-related human activities which can include storage, preparation, consumption, and waste disposal, and the identification of features such as burials, gardens, animal pens, and hearths (Terry et al. 2000). Phosphorus at or near background levels are indicative of non-food-related activities such as patio sweeping, high-traffic pathways, and sleeping areas (Barba and Ortiz 1992; Parnell, Terry, and Sheets 2002).

Background P concentrations in occupation surfaces

Human activities can either increase the P content of soils and floors as organic materials are gathered and processed, or depress the P levels by using materials that were naturally low in P to construct dwelling floors and plaza surfaces. Collection of natural control soils outside of a settled area may not provide appropriate background concentrations of anthropogenic elements. Natural soils likely contain higher levels of P and other elements than excavated fill or plaza stucco derived from burnt limestone. Some researchers have estimated the background element concentrations of the occupation surface by calculating the average concentrations of a portion of samples that were lowest in P concentration (King 2008; Dahlin et al. 2007; Parnell et al. 2001; Terry et al. 2004). The soil and floor samples lowest in P and

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trace elements represent areas of lowest chemical enrichment by ancient human activities.

Soil P fixation

Phosphorus in soil exists in three pools of solubility or plant availability (Hopkins 2015). The dissolved phosphate pool is found in soil solution and is available for uptake by plants and microorganisms. The pool of labile P includes weakly sorbed inorganic phosphate ions, soluble P minerals, and readily decomposable organic P compounds that slowly release phosphate ions to the soil solution during the course of a growing season. The largest pool of soil P is the nonlabile or fixed P that includes strongly sorbed P, phosphate minerals of very low solubility, and P contained in humus molecules that are highly resistant to decomposition and mineralization of P. Phosphorus that is deposited in the soil by human activities eventually becomes fixed, which means that it is strongly sorbed, bound or highly insoluble, and thus can be preserved in the soil for centuries as a marker of those ancient activities.

The analysis of P is a useful tool in geoarchaeological study because it is fixed in a wide range of soils. Precipitation and sorption of P occurs rapidly in soils and floors due to equilibrium chemistry. The soil solution can only hold a finite amount of dissolved P. The reverse reaction (solubilization of precipitates and desorption of labile P) also occurs, with P coming back into soil solution. The rate of this reaction accelerates when nonequilibrium conditions exist due to P being removed from soil solution.

Phosphorus fixation is defined as the formation of solid phase P compounds formed by chemical precipitation reactions or strong adsorption to soil minerals. In neutral pH soils to alkaline soils, several calcium (Ca) phosphate minerals form. The greater the interaction of P with Ca, the lower the solubility of the mineral. Eventually the highly insoluble rock phosphate mineral known as apatite forms in the soil. The high calcium carbonate (CaCO_3) levels in some soils and especially in lime stucco floors promotes P sorption on particle surfaces and increases the precipitation of soil solution P as Ca–P minerals (Hopkins 2015). Phosphorus combines with Ca and magnesium (Mg), which are typically

found at high concentrations in alkaline soils. These Ca and Mg phosphates are poorly soluble at high pH. In neutral to acid soils, phosphate ions react with iron (Fe) and aluminum (Al) to form highly insoluble Fe and Al phosphate minerals. Examples of these fixed phosphate minerals include strengite ($\text{FePO}_4 \cdot 2\text{H}_2\text{O}$), vivianite ($\text{Fe}_3(\text{PO})_2 \cdot 8\text{H}_2\text{O}$), and variscite ($\text{AlPO}_4 \cdot 2\text{H}_2\text{O}$).

History of phosphate testing in archaeological settings

Geochemical analysis of ancient activity areas in archaeological studies extends back to the early 1930s and 1940s in Europe, when Swedish agronomist Olof Arrhenius reported the relationship between elevated soil phosphate levels and sites of previous human occupation. Activities such as food preparation, storage, disposal, animal confinement, and the manuring of fields and gardens leave distinct chemical impressions that can remain relatively immobile in the soil for centuries. Soil samples collected prior to excavation can be analyzed and chemical patterns determined, and mapped, to prospect for archaeological features of interest. An example of soil phosphate prospection is a shovel-test survey in an effort to locate a lost historic farmstead in northwest Virginia (Rypkema et al. 2007). The patterns of phosphate accumulation in occupation soils and floors revealed ancient ceremonial and household activity areas at Templo Mayor in central Mexico (Barba et al. 1996). King (2008) conducted geochemical analysis of residues in Post-classic floors and waste deposits to provide information on food-sharing, commensality, and household social organization in coastal Oaxaca, Mexico.

The karst topography of the Maya Lowlands provides an ideal setting for phosphate investigations. Calcium is naturally rich in the thin soils surrounding the ancient Maya settlements and is the means for P fixation in these soils. Plaza floors, causeways, and the floors of elite households and buildings were plastered with stucco, produced from burned limestone, which is naturally low in P.

Extractable P analysis of soils and floors of both ancient and contemporary households in

Mesoamerica have demonstrated that household activity areas contain different levels of P that have helped to identify areas of food preparation, consumption, storage, waste disposal, sleeping quarters, workshop activities, and ritual and funerary activities (Terry et al. 2004). Geochemical analysis of soil phosphate prior to excavation has been used at Piedras Negras, Guatemala and other sites as a prospection tool to identify waste middens and other important features (Terry et al. 2000). Similarly, Parnell et al. (2001) reported a significant positive correlation between sherd density in test pits and surface soil P concentrations. At Cerén, El Salvador, Parnell et al. (2002) found the highest P concentrations (>50 mg/kg) in middens, while the lowest P concentrations were discovered in the samples from pathways (about 5 mg/kg), where constant foot traffic and sweeping prevented P accumulation. Thus, well-used pathways and heavily used activity areas tend to be low in extractable P. Ceremonial, feasting, and marketplace activities in open plazas have recently been identified by chemical analyses of gridded soil samples (Dahlin et al. 2007).

Phosphorus analyses

There are several laboratory and in-field methods to determine phosphorus concentrations that have been used in archeological studies. These analyses are modifications of standard soil analyses used in determining the total P content of the soil or the extractable P that is related to plant uptake in agriculture.

Total phosphorus

Total P can be determined with chemical digestion of soil. This method requires the use of harsh chemicals, nitric and perchloric acid, and would be limited to a laboratory setting. The digestion of soil is also time- and labor-intensive. Total P analyses may provide information on human activities, but the natural mineral constituents of soil and floor particles may overwhelm the trace levels of P deposited by human activities (Parnell et al. 2001; Coronel et al. 2014). Total digestion with nitric and perchloric acid solubilizes all of the mineral and organic P constituents that are,

for the most part, neither plant available nor anthropogenic. Parnell and colleagues (2001) demonstrated that high concentrations of total P levels from a group of 35 samples from an ancient occupation surface at Piedras Negras were two orders of magnitude greater than the levels of P extracted by dilute acid. The total P analysis includes phosphate minerals that are naturally sorbed by soil particles, whereas anthropogenic P would most likely be found adsorbed to the surfaces of soil particles. Relative concentrations and spatial distributions of chemical residues are key to the identification of human activity areas.

Extractable phosphorus

Soil scientists often conduct soil nutrient availability tests to estimate the amounts of resident P that the soil can provide for crop growth. Soil samples from the field are extracted with various dilute acid or alkaline solutions that remove the pools of soluble and labile P that are likely to provide plant nutrition during the growing season. Dilute acid and mild alkaline extraction procedures remove a portion of the phosphorus adsorbed on the surfaces of soil particles. Variations of P extraction methods have been designed and simplified to use in the field laboratory, (Rypkema et al. 2007; Terry et al. 2000).

The extractable P concentrations vary greatly with the type and strength of the extracting solution. In each extraction procedure, the portion of phosphorus analyzed is affected by soil acidity or alkalinity, organic matter percentage, clay content and soil type, and other physical and chemical properties of the soil. For these reasons, the magnitude of extracted P concentration differs with the procedure and with soil type and geographical origin.

Terry et al. (2000) and Coronel et al. (2014) subjected soils of household middens, patios, and pathways from Piedras Negras to three different extraction procedures and two total P analysis procedures, including nitric and perchloric acid digestion and X-ray fluorescence (pXRF). While the three extraction procedures identified high soil phosphorus levels surrounding household middens and low phosphorus concentrations in patio and pathway soils, the Mehlich II dilute acid extraction provided the greatest percentage

difference in concentration between background samples and midden samples. The greater contrast between midden and average P values determined by the extraction techniques illustrates the fact that anthropogenic P is most likely to be in the form of extractable P absorbed on the surfaces of soil particles rather than the total P contained within the mineral and organic parent materials of the soil (Coronel et al. 2014). Several studies have shown that the extractable phosphate procedure is not only better because of more interpretative detail in the resulting chemical patterns, but it is also more cost-effective and functional in both formal and field laboratory settings.

SEE ALSO: Archaeological Sciences; Archaeometry; Augering; Chemical Mapping; Chemistry in Archaeology; Portable X-Ray Fluorescence Spectrometry (pXRF); Soil Chemistry in Archaeology; Soil Survey

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Soil Survey

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Contemporary applications of soil survey in archaeology intersect the boundaries of theoretical interdisciplinary geoarchaeology (see GEOARCHAEOLOGY) and increasing methodological emphases on macro- rather than micro-level scales of analysis. Soil survey has been used in soil mapping since the early 1700s, but spatial representation of soil attributes in documentary evidence had considerably earlier origins. Documentary records show that soil properties had been applied to delineate land ownership as early as the fourth century in China (Brevik et al. 2016). However, its widespread use in pedological investigations of soil distribution and the relationship between landscape and cultural interaction dates back to the early nineteenth century. The creation of nationalized soil survey programs in the twentieth century (Brevik et al. 2016) indicates that soil survey had become an essential component to soil science and research at both the academic and government levels (Holliday 2004). Holliday (2004) argued that soil survey and mapping have been relatively underutilized in geoarchaeological investigations. However, geochemical investigations of land-use patterns within the last decade have increasingly relied on soil surveys to inform differential spatial patterns of past human–environmental interaction (Wilson, Davidson, and Cresser 2008) (see ENVIRONMENTAL ARCHAEOLOGY). Soil survey and mapping has seen an infusion of new digital methodologies emphasizing the quantitative power of spatial soil prediction (Gessler et al. 1995; McBratney, Mendonça Santos, and Minasny 2003; Scull et al. 2003; Mulder et al. 2011; Demattê and da Silva Terra 2014).

Traditional soil survey requires the application of three different methods in order to properly record spatial variations in soil series. First, one must conduct a preliminary, direct observation of landscape data and corresponding soil

characteristics. This involves investigating aerial photographs or satellite imagery of the study area to analyze known geological features, vegetation changes, and their impact on the distribution of potential soil classes. Next, soil attributes must be observed in the field and used to construct a generalized model of soil variation (Scull et al. 2003). Holliday (2004) defines these attributes as a soil series. Each soil series is investigated based upon such characteristics as: type, thickness, color, texture, structure, pH, and mineralogy (Holliday 2004). Finally, a soil survey must use known distinctions in soil series to create a generalized spatial model of soil association across the landscape, capable of predicting variation in unobserved areas (Scull et al. 2003; Holliday 2004).

National soil mapping programs employ this qualitative means of soil survey to record variability in soil resources. Soil surveys have been used for a considerable number of non-archaeological applications, including land-use planning, soil conservation, and land evaluation. These surveys produce maps at differing scales, which could prove problematic when creating regional evaluations of soil attributes. However, soil surveys have traditionally collected a variety of information regarding soil properties, which is useful to geomorphological and geoarchaeological investigations.

Specifically, loess thickness and origin, soil texture, and soil erosion have proved particularly helpful (if underutilized) in evaluating the influence of geomorphology on the preservation of archaeological data. Theoretically, soil scientists and geoarchaeologists have traditionally been divided on how they approach spatial soil relationships. Pedologists have conducted soil surveys that emphasize the vertical dimensions of soil rather than spatial, horizontal variability (Holliday 2004). Holliday (2004) argued that soil survey is thus problematic for reconstructing past relationships between geomorphology and the spatial patterning of archaeological material.

Archaeology's deep-temporal understanding of soil development and its historical implications may be its greatest contribution to the creation

of future soil maps and the refinement of soil survey methods. Holliday (2004) emphasized four distinct uses of soil surveys in archaeology. First, soil surveys have proved useful in site analysis. Often, soil surveyors have recorded potential sites and their location during initial surveying. At other times, the mapping of drainage has helped archaeologists locate the most likely locations in which to find additional sites. Second, distributions of soil series have been used as a predictive tool to locate sites based upon known locations of other sites relative to certain soil series. Archaeologists have utilized soil maps to predict cultural areas based upon frequencies of soil series. Third, cultural resource management (CRM) has driven increased demand for the recording of spatial soil relationships based upon differential geomorphology. Fourth, soil surveys have been used by archaeologists to analyze the distribution of landforms and relative age of the landscape (Holliday 2004). Soil surveys have thus been a cornerstone of historical ecology studies. Archaeologists use variation in soil attributes relative to geomorphology to inform the degree and legacies of ancient and historic land-use practices.

Geochemical approaches are often combined with traditional analyses of soil surveys to further elucidate the spatiality of human activity patterns. Wilson et al. (2008) conducted multi-element analyses of soil samples to evaluate inter-site variability in activity patterns at various abandoned farms in the UK. Wilson et al. (2008) concluded that human activity areas can be determined by analyzing variations in concentrations of Ba, Ca, P, Zn, Cu, Sr, and Pb. Wilson et al. (2008) found that Hg and Pb concentrations can best identify areas of craft production, while Sr and Ca can identify agricultural areas, and K, Rb, and Th can indicate settlement areas. Soil survey informed inter-site variability in soil series, geomorphology, and hydrology, which can affect the spatial distribution of elemental concentration, conflating the role of archaeological activity patterns. Soil survey allowed Wilson et al. (2008) to comment on the effect that postdepositional soil-forming processes versus anthropogenic element loading had on the overall picture of contemporary landscape conditions.

Geoarchaeological investigations in Antigua, West Indies, use soil survey and geochemistry to evaluate the long-term landscape legacies

of nearly 300 years of sugarcane monoculture. This study uses geomorphology and elemental signatures of intensive agricultural production to contribute more generally to the archaeological understanding of land degradation resulting from agricultural abandonment. Soil survey is being used to inform the degree of contemporary landscape erosion, in efforts to help mitigate landscape instability. Soil survey has also contributed greatly to archaeological investigations analyzing the impact of past human–environmental interaction on the lived experiences of contemporary populations.

The use of soil survey and mapping in archaeology has been cautioned by Holliday (2004) in accordance with two primary confounding principles. The generality of soil maps limits their utility for archaeological investigations. Holliday (2004) argued that a lack of consistency in scale severely limits the use of soil survey in analyzing site-specific research questions. Generalized grouping of soil classes across the landscape also confounds the complexities of spatial distribution. Soil surveyors tend to group soils into a limited number of different classes based upon associations between their attributes. For this reason, Holliday (2004) noted that boundaries between soil classes on maps are rather arbitrarily and subjectively constructed. Therefore, any archaeological site that is smaller than the scale of the map will be hindered by these problems. Micro-scale investigations of landscape complexities in archaeology are thus limited. Holliday (2004) alluded to the greater applicability of soil survey in macro-scale investigations.

Soil survey in archaeology has begun to shift from qualitative descriptions of soil attributes to quantitative analyses and predictions of the spatial distribution of soil series. McBratney et al. (2003) argued that the field began to transition in the last 20 years from reliance on knowledge-based modeling. Gessler et al. (1995) prominently called for the creation of a statistical model to relate geomorphological features with variations in soil attributes. This process included the development of a new systematic field-sampling strategy to construct a more accurate soil–landscape model. Gessler et al.'s (1995) model was a visible shift away from the traditional view of soil profiles in pedology to a statistical

representation of soil layers defined more commonly among geomorphologists (a theoretical shift from vertical to horizontal soil distribution). This new approach attributed environmental factors as a leading driver of surface and subsurface soil variability. Gessler et al. (1995) promoted a nonrandom soil sampling strategy in areas characterized by landform variability. This provided a uniform means of statistically predicting soil distribution in areas without variable topography. Both Gessler et al. (1995) and McBratney et al. (2003) called for a scientific rather than subjective means of defining soil series and distribution. New digital soil mapping techniques heed this recommendation, but utilize remote sensing methods to reduce field sampling.

Remote sensing (see AIRBORNE REMOTE SENSING) in soil survey has increased in applicability over the last decade. Remote sensing has been employed to reduce the confounding problems of scale and generalization outlined by Holliday (2004). Specifically, Mulder et al. (2011) argues that the most appropriate application of remote sensing in soil survey is to improve incomplete or inaccurate soil distribution data and integrate regional soil surveys into global soil databases. Remote sensing can accurately determine soil attributes such as mineralogy, texture, and organic carbon. Optical spectroscopy is the most useful remote sensing technology for soil surveying purposes. However, Mulder et al. (2011) argues that remote sensing of soils still lacks a cohesive methodology to incorporate statistical interpolation holistically with measurements of soil attributes.

Remotely sensed soil data is being employed in the creation of digital soil maps, which can more accurately define the boundaries between soil classes based upon quantitative rather than qualitative analyses of soil attributes (McBratney et al. 2003). Spectral reflectance of soils and other environmental features are being employed in order to create global maps of soil distribution without having to rectify scaling issues. Digital soil maps are being used to create predictive soil models, which help to elucidate the complex interactions between soils and their biophysical and biogeochemical functions (Scull et al. 2003). Scull et al. (2003) argued that these new predictive models have greater implications for the field of soil science, potentially informing new insights

into the role of soil formation processes in spatial soil distribution. However, the most profound contribution of predictive soil maps and digital soil maps more generally is their ability to use raster grid networks to display spatial soil variation more accurately than choropleth maps.

New methods in soil survey and mapping represent advancements in analyzing spatial variability in soil series using remote sensing techniques, and in analyzing subsurface variability using reflectance spectroscopy (Demattê and da Silva Terra 2014). Brevik et al. (2016) calls for soil survey and mapping to better integrate remote sensing, geographical information systems, and on-site geophysical information in the future, in order to better predict soil distribution and validate current soil-landscape models. Brevik et al. (2016) argues that soil survey is becoming increasingly useful in helping to answer questions regarding land-use planning, environmental concerns, energy security, food security, water security, and human health. Soil survey and mapping was once the domain of soil science research, but it is becoming increasingly important to the interdisciplinary analysis of the environmental conditions affecting the lived experiences of past and contemporary populations.

SEE ALSO: Airborne Remote Sensing; Environmental Archaeology; Geoarchaeology

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Sonar and Sidescan Sonar

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Sonar technology for maritime archaeology

Sound navigation and ranging (sonar) systems have been increasingly used in support of maritime archaeology since the 1960s. Their operation is based on the principles of underwater sound propagation and the concept of acoustic remote sensing. With their use, physical properties of underwater features of archaeological interest can be recorded from a distance by their interaction with sonar-generated acoustic waves. The sidescan sonar has been the most commonly used marine geophysical instrument in maritime archaeology, and it still remains a significant tool for seafloor mapping, due to its portability, ease of deployment, and low-cost availability.

Sonar systems and acoustic remote-sensing techniques found wide acceptance among scientists, researchers and engineers by reason of efficient propagation of acoustic waves in the sea. Particularly, sonar systems found applications in maritime archaeology from the early years of their commercial availability, around the 1960s, leaving behind some disadvantages of diving operations. With the use of sonar, large sea areas can be explored rapidly and deep-water investigations can be conducted beyond the depth or duration limitations of scuba diving. Water turbidity, currents, adverse environmental conditions, and shipping traffic can all restrict diving operations, but can little affect acoustic remote-sensing methods. Besides, using sub-bottom profiling sonars, a non-invasive investigation beneath the seafloor is possible. Beyond the use of sonar for detection of underwater features of archaeological interest, sonar imaging techniques provide information

about natural processes that have governed the underwater environment through the millennia. Archaeologists can then reconstruct sites and better understand their archaeological potential, the conditions of historical events at sea, and the interactions between the environment, human activities, and the archaeological material. Therefore, sonar data can help the archaeological site management through the prediction of site evolution. Nonetheless, the use of sonar has certain limitations related to cost, logistical issues, time constraints for availability of quality-controlled data, and their specifications against the survey objectives. Furthermore, different kinds of sonars provide data for specific applications, and process acoustic signals affected by unpredictable phenomena, like tides and water-column temperature gradients, that need to be accurately compensated for. This has to be done by qualified surveyors who also have to plan the fieldwork strategy and determine the sonar recording parameters. Therefore, the quality of the sonar outcome is largely related to the surveyor's level of competence, the survey specifications followed, and understanding of the archaeologists' objectives.

A full interpretation of sonar records requires expertise in the fields of marine geophysics, hydrography, marine geology, and underwater acoustics. However, a basic understanding is feasible, provided that basic knowledge of sound propagation and system operation exists. The active sonar systems accommodate underwater transducers emitting acoustic pulses in the sea in the form of acoustic waves or pressure fronts. The frequency of operation of a sonar system is equal to the number of pressure fronts transmitted per unit time. The transmitted acoustic signals interact with the water volume and features in the water column, as well as with seabed features, and are refracted, spread, scattered, attenuated and reflected in different directions. Only a portion of the signals return back to the transducers as echo or backscatter. The returned acoustic energy is then converted to electric signals, which are processed and rendered graphically in a display such that the variability of the returned acoustic energy represents the variability of physical

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properties of the seabed. From the two-way travel time of acoustic signals, quantitative results can be achieved, often related to seafloor bathymetry and the georeference of features. Passive sonars only receive signals radiated by underwater sources, hence only provide underwater communication and telemetry solutions. A full presentation of the principles of underwater sound can be found in Urlick (1983).

The sidescan sonar

Sidescan sonars are widely used in underwater archaeology for imaging objects of archaeological interest lying on the seafloor and for mapping seafloor geomorphological features that improve the site understanding. Some of their common applications include mapping of submerged landscapes, detection and visualization of modern and ancient shipwrecks, artifacts, and features related to human activities. They also provide information about the seafloor geomorphology and the texture of the sediments covering the seafloor. This kind of information is useful for assessing the impact of underwater natural processes and of human activities on the underwater cultural resources, and hence for assessing the site evolution.

A sidescan sonar configured to be deployed from a surface vessel typically comprises a transceiver processing unit, a towfish where a pair of transducers are housed, and a tow cable for underwater tow and for sound signal and data acquisition control (see Figure 1). The towfish can either be towed behind the vessel or pole-mounted. Sonar control can be achieved through a workstation linked with the topside processor. Since all explored features have to be precisely positioned, a marine GNSS (see GPS (GLOBAL POSITIONING SYSTEM)) has to feed the system with positional data.

The towfish transducers emit acoustic pulses in the form of beams, each side of the towfish. These acoustic signals are partially absorbed in the seabed and partially scattered or reflected off the seafloor and from objects lying over the seafloor. Only a small amount of the signals finally scatter back to the transducers, and this contributes to the imaging process. The side-

scan beams are formed wide across-track and narrow along-track (see Figure 2a), so the sonar senses the backscatter from a narrow strip of the seafloor, except for the nadir sonar sector.

The sonar beam angle (thereafter the along-track width of the ensonified stripe) dictates the along-track resolution of the sonar which corresponds to the sonar ability to resolve between two objects in the along-track direction. The across-track resolution depends principally on the electroacoustic specifications of the pulse length (Quinn et al. 2005) and corresponds to the sonar ability to resolve between two objects in the across-track direction. The forward movement of the boat leads to a full insonification of the seafloor each side of the boat along its course and within the sonar horizontal range, except for the nadir sector. The intensity of the received acoustic backscatter depends on the angle of incidence of the acoustic signal to the seafloor and the physical properties of the seafloor. Thus, acoustic backscatter provides information about the variability of the seafloor slope, morphology, roughness, as well as the variability of material and roughness of objects over the seafloor. On a sonar record, rocky seafloor is showing higher backscatter than fine-grained sediments, an upslope seafloor is showing higher backscatter than a downslope, artifacts made of steel are showing higher backscatter than softer material, and areas of the seafloor not ensonified due to sonar geometry and seafloor morphology are represented as acoustic shadows. Acoustic shadows often help the interpretation of records in three dimensions rather than masking information. It is up to the sonar data processor to choose to represent the relatively high backscatter with either relatively light or dark tones. Accordingly, shadows are represented with either black or white color. An insight into the sidescan sonar theory of operation and record interpretation can be found in Blondel (2009).

Figure 2b is a snapshot from a sidescan sonar display, showing raw data from the sonar's port beam. The dashed line along the right edge of the display indicates the towfish past-track over the seafloor with its latest position top right. The white vertical strip parallel to the dashed line assumes no data and corresponds to the travel time of pulses through the water column.



Figure 1 A typical sidescan sonar system. From left to right, the sidescan topside unit, towfish and tow cable.
Source: Kongsberg Maritime, PulSAR sidescan sonar.

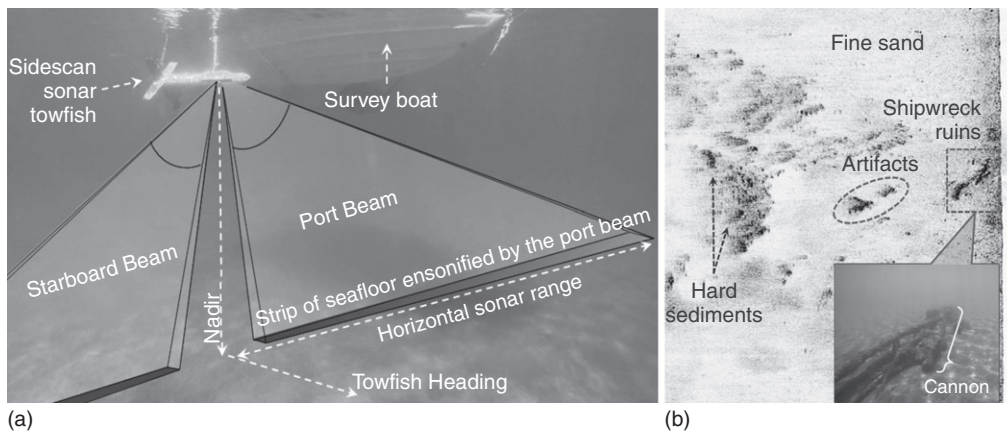


Figure 2 Sidescan sonar operation. (a) Theory of operation. Photo: Panagiotis Gkionis. (b) Sample sidescan record (port beam only) showing shipwreck ruins, artifacts, and the seafloor texture variability.
Source data: The Evolved GE.N.E.SIS project.

The sonar record highlights scattered archaeological material and the seafloor sediment distribution. Inset in the sonar imagery is the photographic depiction of a recorded cannon. It is evident that limitations in object identification exist, and these are largely related to sonar specifications and geometry. High-frequency systems (400–900 kHz) of short pulse width may provide high-resolution outcomes suitable not only for object detection but also for object identification, but only in short ranges. Figure 3 shows the sidescan record of an ancient shipwreck that has been ensonified by various frequency pulses, and thus exhibiting different resolutions.

In the sidescan sonar display, the y axis represents the track of the towfish over the seabed, while the x axis represents the two-way travel time of the acoustic pulse. The raw sidescan data in both x and y axes is not to scale; the vessel's speed is variable and the travel time of acoustic pulses does not directly represent distance over the seafloor. Archaeologists need to analyze the sonar outcomes scaled and often projected onto maps, where they can correlate the recorded features with findings from other surveys. Also, they often need to study the regional imagery of a site and the spatial distribution of findings. To that end, sidescan data processing is essential and corrections need to be applied to the sonar image. Then data from single lines can be mosaiced and georeferenced, so that ground coordinates

are assigned to displayed features in regional imagery.

Sonar advancements

The need for high-resolution mapping in three dimensions (3D) and exploration of deep-sea energy resources has driven a wealth of sonar technological and methodological advancements. Underwater archaeology enjoys their benefits, deriving a better understanding of trade through the open seas in the ancient world. Submersible technology allows scientists to operate sonars onboard autonomous underwater vehicles (AUVs) or remotely operated vehicles (ROVs) close to the ocean seafloor, and thus acquire high-resolution data transmitting high-frequency signals in that short range. Furthermore, the application of parametric and chirp technology in low-frequency signal generation and processing has helped the improvement of resolution and signal penetration of sub-bottom profiling systems. Signals from these systems penetrate the seabed up to a limiting depth and reflect from the various sedimentological, geological or artificial boundaries, providing high-resolution stratigraphic profiling. The development of 3D sub-bottom profilers allows the 3D reconstruction of buried shipwrecks and site paleogeography. Synthetic aperture signal

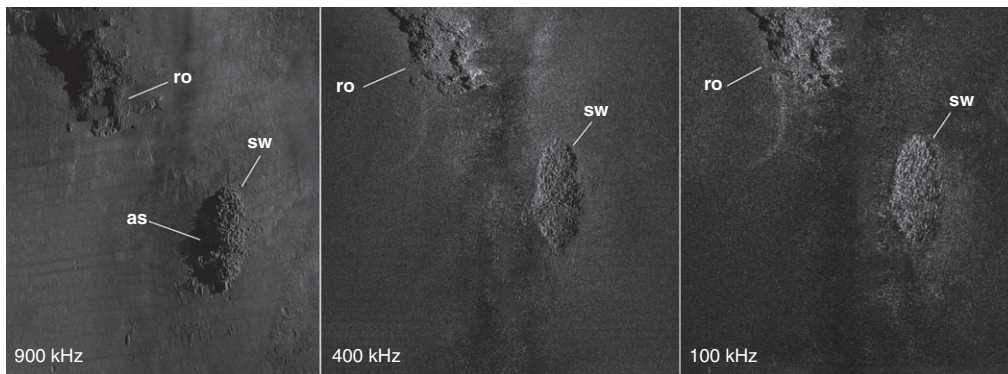


Figure 3 Sidescan sonar records showing an ancient shipwreck (assemblage of amphoras), resting on the seafloor, acquired at different frequencies (100, 400, and 900 kHz). Higher frequencies provide higher resolution. High backscatter, which is attributed to hard substrate, is presented by light tones on records. Low backscatter (soft substrate) is presented by dark tones (modified from Geraga et al. 2015). sw, shipwreck; ro, outcropping rock; as, acoustic shadow.

processing is another advanced technique based on the concept of virtually long transducers for achieving high-resolution imagery regardless of the sonar range.

The most significant advance in sonar technology has been the development of swath bathymetry systems. Two types of such systems exist: multibeam echosounders, which are a direct development of single-beam spot-depth echosounders, and the interferometric sonars, which are a direct development of sidescan sonars. Both are either mounted on a survey vessel or deployed on AUVs/ROVs, providing bathymetric information for a strip of the seafloor as long as up to 12 times the water depth. As the vessel moves forward, they can fully ensonify an area providing a point-cloud of depth soundings so dense that scientists use it to create a 3D model of the seafloor and of objects lying upon it, after proper processing of the acquired data. Backscatter information is also an option, so sidescan imagery can be generated and directly related to the third dimension. Swath bathymetry systems are used for detection of features of archaeological interest and for gaining a better understanding of the dominant natural processes of a site.

The great potential of sonar technology in support of underwater archaeology can be revealed through the synthesis of outcomes from a combination of applied sonar techniques. Geographical information systems (GIS) are digital platforms where sonar outcomes can be visualized, fused and correlated in four dimensions (including time) for spatial and temporal analysis of findings.

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Synthetic Aperture Radar

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Since the 1970s, synthetic aperture radar (SAR) data have been used in various ways in the study of archaeological sites. SAR transmits a series of microwave pulses towards the desired ground image swath, and then coherently receives the backscattered echoes. The returned signal data are then processed into high-resolution imagery. Some of the advantages of SAR, such as all-weather imaging, foliage and dry sand penetration, topographic and survey mapping, sensitivity to man-made features, and disturbance detection, have been employed to further archaeological studies.

Twenty-seven years after Carl Wiley at Goodyear Aircraft Company invented SAR, the first civilian spaceborne SAR was launched into Earth's orbit onboard the ground-breaking NASA Seasat satellite in 1978. This L-band (23.5 cm wavelength) SAR demonstrated many of the capabilities that have since led to the launch of over 20 civilian spaceborne SARs, such as ocean observations, geological mapping, and dry surface penetration; and also the use of interferometric SAR for mapping surface deformations (Elachi 1980; Gabriel, Goldstein, and Zebker 1989). An airborne prototype for the Seasat SAR (and other NASA SAR missions such as the Venus Magellan Radar) flew onboard the NASA Ames CV-990 Airborne Laboratory during the 1970s and 1980s, and conducted the first attempted archaeological application of SAR by overflying northern Belize and virtually all of the Petén region of Guatemala (Adams, Brown, and Culbert 1981). The objective was to investigate whether foliage penetration would enable mapping of ancient roads, causeways, and other manmade structures. While the results were not conclusive, these same objectives would guide many future archaeological experiments with SAR.

In 1981, the Shuttle Imaging Radar-A (SIR-A) flew on the second flight of the NASA Space Shuttle Columbia for a short duration (only two days in orbit) technology demonstration. The L-band SAR images of the Egyptian Sahara seemed to indicate a terrain carved by running water; however, the surface landscape was dominated by windblown sand. These SAR images were found to have revealed previously unknown buried valleys, geological structures, and possible Stone Age occupation sites. The locations of these drainage networks provided a geological explanation for the locations of human habitation (McCauley et al. 1982). Indeed, recent work shows repeated human occupations of the Sahara during wetter phases of the climate.

Figure 1 shows a SIR-A image overlaid upon an optical Landsat MSS image and illustrates the starkly different appearance of SAR and optical imagery under these conditions. Field measurements showed that the “radar river” features were covered by a thin layer of dry sand (depths sometimes greater than 1 m) (Elachi, Roth, and Schaber 1984). SAR imagery from subsequent spaceborne instruments such as the NASA SIR-C SAR, the Japan Aerospace Exploration Agency (JAXA) JERS-1, and JAXA ALOS PAL-SAR SAR instruments, further identified these paleodrainage channels. Imagery from higher frequency SAR systems such as the Canadian Space Agency (CSA) RADARSAT-1 (a C-band, 5.5 cm wavelength SAR instrument) was also found to be sensitive to the presence of these sand-covered drainage channels. The discovery of the locations and the subsequent dating of these paleodrainage systems have a clear value for understanding past environments and climates of northern Africa, including their impact on human habitation.

Following the opportunistic polarimetric and multifrequency SAR imaging of the Angkor Wat site in Cambodia by SIR-C in 1994, a more extensive imaging campaign was conducted by a NASA airborne SAR called AirSAR operating on NASA's DC-8 flying laboratory in 1996 and 2000. Operating in a topography mapping mode, where data from two antennas are interfered to

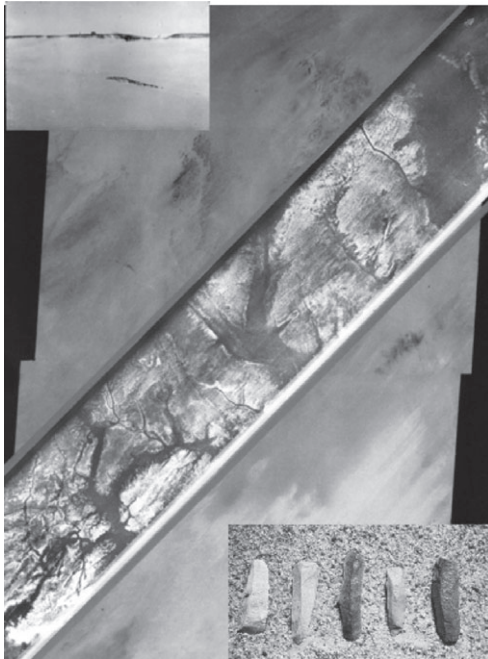


Figure 1 This figure shows a SIR-A image of the western desert of Egypt laid upon a Landsat MSS image. The VNIR Landsat image shows the present-day surface sand cover, while the radar image shows a fluvial landscape from wetter climatic episodes in the Sahara. Upper left inset shows from the ground the appearance of a “radar river”. Note jeep on riverbank for scale. Lower right inset shows typical artifacts collected. SIR-A image swath width is 50 km.

Source: Chapman and Blom (2013). Courtesy NASA/JPL-Caltech.

estimate ground elevations, the data revealed new structures and significantly enhanced regional understanding (see Figure 2) (Moore, Freeman, and Hensley 2007). This mapping campaign showed that highly accurate and fine-resolution topography data could be very useful for the identification of manmade structures, even in the presence of confounding topography from vegetation and other natural features. It was soon discovered that airborne laser scanning technology (lidar) could be as or more effective than SAR at mapping microtopographic features (see AIRBORNE LASER SCANNING AND LIDAR). This technique has since revolutionized the use of remote sensing data in archaeology.

Fully polarimetric, multifrequency observations by SAR continue to be used in other investigations, such as developing predictive models for potential site locations (Comer and Blom 2007), and in continued work to investigate whether foliage penetration would enable mapping of ancient roads, causeways, and other manmade structures. SAR has also been used for producing large-scale archaeological surveys. The advantage of using SAR is its sensitivity to certain geological features such as lineaments and sub-pixel manmade features.

Very high resolution (<1 m) observations are possible from space using X-band (3.1 cm wavelength) SAR systems such as TerraSAR-X and COSMO SkyMed satellites. Using the TerraSAR-X Staring Spotlight mode, Balz et al. (2015) were able to identify small grave mounds in China. One of the advantages of this type of high-resolution SAR imagery over readily available high-resolution optical imagery is its inherent all-weather imaging capability.

During an airborne campaign to South America in 2013 and 2015 by NASA’s UAVSAR, an L-band and fully polarimetric airborne SAR, data were collected over The Lines and Geoglyphs of Nasca and Pampas de Jumana World Heritage Site in Peru. Geoglyphs, created by the Nasca people by moving small stones to form geometric as well as biomorphic figures, are found across a wide expanse within in this dry desert landscape. Since SAR is sensitive to the scattering behavior of these small stones, some of the geoglyphs are readily discernable in SAR imagery if the resolution is sufficiently high. Also, since there is little vegetation or weather affecting this area, the magnitude of the interferometric coherence from interferometric SAR (InSAR) was found to be an indicator of vehicular and even foot traffic within this fragile protected zone. Figure 3 illustrates what this type of data looks like, and shows three unpaved roads within the protected zone of the Nasca World Heritage Site that have been driven upon between the time of the observations (March 2013 to March 2015). Power lines are in the upper right-hand portion of the image, where the decorrelation stands out due to the movement of the power lines between observations. This result demonstrates the value of interferometric SAR data in some areas, for the protection and

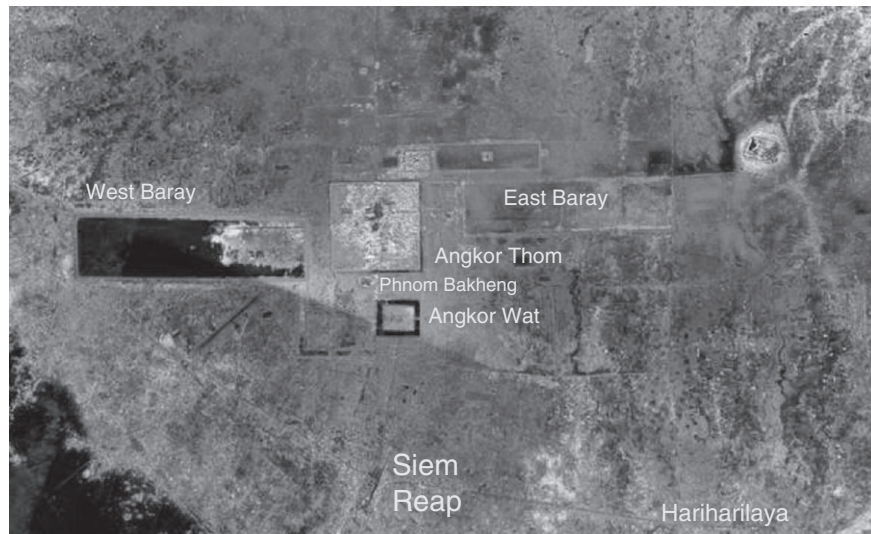


Figure 2 AIRSAR digital elevation map of the Angkor area in Cambodia, showing major Barays and ancient infrastructure. The terrain slopes gently from top to bottom, which is indicated by the shading. Source: Courtesy NASA/JPL-Caltech.



Figure 3 Calibrated magnitude of the coherence image from UAVSAR overlaid in Google Earth. Black corresponds to decorrelation, typically due to disturbance between the two observations (March 2013 to March 2015), while grey and light grey correspond to areas with minimal decorrelation. The horizontal line in the center of the image indicates 100 m. Source: Chapman et al. (2015), UAVSAR imagery. Courtesy NASA/JPL-Caltech.

management of sensitive archaeological sites (Chapman et al. 2015).

In the future, freely available and widely collected data from the ESA Sentinel-1 SAR satellites and the NASA-ISRO synthetic aperture radar will enable widespread use of SAR data for many endeavors, including those in archaeology.

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SEE ALSO: Airborne Laser Scanning and Lidar

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Terrestrial Excavation

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If excavation in general is defined as the exposure and removal of deposits, then terrestrial excavation in archaeology can be seen as carrying out this process systematically on land to generate data relevant to the interests of the discipline, that is, the study of past human societies and their environments. All such excavation involves removing the layers and features of a site in the reverse order to which they were laid down, in the process creating a range of descriptive, spatial, and chronological data. Yet this work can be approached in a variety of ways, depending on its extent and form (open area versus boxes versus pits), the definition of deposits (by individual contexts versus the planum/schnitt method), and institutional setting (rescue/salvage work ahead of modern development versus research projects investigating otherwise unthreatened sites). Some of this diversity is explored below.

Today, excavation is mostly considered the principal way in which archaeologists gather evidence. Yet, historically, the discipline started by *collecting* material culture, first to satisfy the aesthetic needs of social elites, notably within Europe, then, later, to elucidate social development, often as part of a project to create identities within emerging nation states: to give them a sense of “their” past.

This collection phase led to the plotting of monuments: *mapping*. Investigation of their distribution threw up gaps across the landscape: Were these significant or simply a product of buried or destroyed features? From here, it was only a short step to *excavating* to check patterning, in the process gathering finds to add to existing collections. The move from collecting to mapping to excavating happened at different times in different parts of the world, but the general sequence is almost ubiquitous. Understandably, the actual form of intervention varied greatly: for

example, wall chasing to confirm building plan form, or digging, often fairly randomly, into the centers of mounds to find burials and recover associated grave goods.

In order to play its growing role in charting social development, excavation needed to move beyond the notion of a past constructed in terms of individual monuments, frozen in time, to focus on generating evidence concerned with sequences of change. This, in turn, meant attending to any archaeological stratigraphy revealed in the course of such work. In western Europe, this approach was increasingly evident in the course of the nineteenth century, for example, with Pitt-Rivers (Bowden 1991), but had its clearest expression in the work of Sir Mortimer Wheeler in the twentieth century (Wheeler 1954) and his promotion of box excavation. This attempted to reconcile the needs for vertical control of sequence, as recorded in section drawings of baulks (the unexcavated stratigraphy between boxes), with the requirement to elucidate plan form. Under the influence of colonial rule, this approach spread to different parts of the world, and is still used on many archaeological sites today.

Box trenches were, however, poorly suited to recording non-rectangular features and buildings: Baulks sometimes obscured stratigraphic relationships, while, within even quite small excavated areas, not all of the layers reached their sides, to then appear in the section drawings. Thus, “open area” excavation techniques were developed, at first, unsurprisingly, on sites with irregularly distributed or asymmetrically positioned features, in particular in Scandinavia under the influence of Axel Steensberg, then spread further, for example by Gerhart Bersu. This change in technique also involved an advance in the complex detail involved in recording plan form *in extensio*, for example with the use of color drawings, now extended through the use of the global positioning system (GPS) in conjunction with digital photography.

Today, there is no one dominant approach worldwide (Carver 2011, Figure 4.8): In some regions, mostly western Europe, “open area”

techniques prevail; across much of southern and eastern Asia, “box excavation” is more prominent; and in the Americas and Australasia, smaller “pit excavation” prevails. The differences seem to relate to the character of the sites under investigation and the research agendas being applied to them.

Whatever the extent of exposure of archaeological strata in each case, however, these approaches involve attempting to define the limits of each distinct deposit, then recording and removing it. In contrast, across eastern Europe and northern Asia, most sites are excavated in arbitrary levels, the so-called *planum* or *schnitt* method. This is best deployed where deposit boundaries are indistinct, and thus stratigraphic divisions have to be imposed. Such sites are clearly more common in the latter regions (or a mixture of systems is often needed: Hester, Shafer, and Feder 1997, 88; Carver 2011, Figure 1.1).

Excavation practice is not only affected by site characteristics but also by developments beyond archaeology. This includes ideological changes such as the rise of science and Darwinist perspectives, as seen in Lyell’s *Principles of Geology* (1830–33) which, ultimately, had a profound impact on the recording of archaeological sequence. These theoretical advances were, in turn, underpinned by real-world concerns, for example, for Lyell, by the scale of nineteenth-century geological exposures in quarries, canals, and railway cuttings (not to mention light detection and ranging (LiDAR), GPS, carbon dating, and dendrochronology since then, all developed outside our discipline but having considerable significance within it).

Yet it could be argued that social and organizational factors, not ideas or techniques, have had the most lasting impact on excavation work: Pitt-Rivers, a British aristocrat/soldier with the land and resources to carry out his ground-breaking fieldwork in the United Kingdom; and Schliemann, a German industrialist with the money to finance his expeditions and the colonial contacts to ensure they were permitted. These are parochial examples, but the organizational context of excavation has taken on a global dimension from the mid-twentieth century. Up to that point, much excavation was carried out for reasons of research, whether by interested

parties in local groups or governmental institutions such as museums and universities. From the late-1960s, following the long boom in the world economy, threats to the archaeological resource at unprecedented levels were recognized.

These pressures were evident in both rural contexts, where extraction of aggregates and minerals, creation of infrastructure, afforestation/deforestation, and mechanized ploughing impacted increasingly on once “safe” sites, and urban settings, especially historic towns, which saw expansion, high-rise developments, and new transport systems. Their scale and severity required an equally large-scale response from the archaeological community: The need to rescue this heritage by creating an excavation “archive” in place of the site itself was recognized and innovative methods developed in many countries to cater for the variety of new, and often difficult or dangerous, working conditions. Perhaps the most significant result, however, was the creation of a new breed: the full-time, professional excavator.

All excavation involves splitting a site into its component parts (stratigraphic units), each with physical, spatial, and chronological properties. Teams of paid, professional staff created a need to systematize the process. This resulted in a greater emphasis on proforma sheets to hold descriptive information, set rules for gathering spatial data in plan and section drawings, and more orderly ways of holding stratigraphic evidence, exemplified by the Harris–Winchester matrix (Harris 1989).

Recording systems today can be divided between those that are hierarchical, for example recording layers and features, and those that employ “flatter” single-context systems. The stratigraphic units they encounter are mostly deposits, using proformas to record color, composition (particle size and inclusions), compaction, and thickness (their extent usually recorded in the form of a plan). Other proforma are used for cut features, recording orientation, shape, depth, nature of sides and base, and so forth, while some projects will employ sheets designed for masonry or timber features and human burials.

The creation of a fieldwork profession, in response to the impact of modern development, brought excavation solidly within the planning process. In recent decades, this has meant greater

integration with environmental impact procedures and associated legislation, reinforcing the need for early consultation to ensure integration of the roles of the developer (with or without the use of their own archaeological consultant), the curator/cultural resource manager, and the contractor/commercial excavation company.

The focus on assessing impact necessarily places increased emphasis the process of reconnaissance (notably “desk-top” studies and aerial photographic survey), and then ground-based evaluation (whether by nondestructive techniques such as geophysics and surface collection, or by more destructive techniques such as shovel testing, bore holes, and test pits). The objective here, in essence, is to consolidate knowledge of the development area to guide future strategy, perhaps most usefully done when all information is combined in the form of a deposit model (Carver 2011, 121).

These stages—reconnaissance/evaluation/strategy (whether or not they use this terminology)—are encountered in many countries today, albeit stretched over different timescales and emphases. What then happens in terms of excavation fieldwork depends, however, on heritage policy. Some countries use the process to identify their most important sites and then excavate them. Others, and this is more closely aligned with the notion of assessing impact upon a fragile, irreplaceable archaeological resource, see the end result as in-situ preservation of those same “important” sites, and hence aim to generate a mitigation strategy.

Either way, if destructive excavation is agreed as acceptable, such work will require some generic preparations: site safety, spoil disposal, shoring, and so forth. It is also likely, and certainly desirable, for its implementation to pass through a cycle of defining a research agenda; modifying such in the light of reconnaissance and evaluation; and then defining sampling strategies and structured data gathering. Any project will also need to undertake specialist analyses post-excavation to allow interpretation and synthesis, followed by dissemination and archiving. A good excavation project will, almost certainly, end up posing more questions than it started with. Yet it will, hopefully, be in a position to articulate an augmented research agenda and say

how it might be best fulfilled: Research questions should drive the whole fieldwork process.

Any excavation will need financial provisions: Excavation is not only destructive, by definition, but also costly in time and resources (increasing use of digital recording systems may reduce such costs or, better still, free up excavators to spend more time on interpreting their evidence). Resourcing excavation projects varies considerably with national context. The original rescue/salvage excavation work from the 1960s onwards was mostly supported through state funding in various guises. In subsequent decades, under the twin influences of general neoliberal frameworks downplaying the role of state expenditure, and the “polluter (here the commercial developer) pays” principle embedded in most environmental impact systems, some countries have moved towards privatizing the profession. In this brave new world, excavation work is subject to the vagaries of the world economy, seen most obviously in the impact that the 2008 recession in western Europe and North America had on excavators’ employment (Schlanger and Aitchison 2010).

As a result of these changes, excavators today face a series of challenging questions, for example whether our ethical priority is to investigate or to preserve sites. Second, the influence of post-processualism within the discipline, aligned with the material way in which excavators encounter the past (Edgeworth 2006), questions how, and when, we should be interpreting excavated evidence: reflexively, “at the trowel’s edge” (Hodder 2000), or only after post-excavation analysis? Finally, and perhaps of greatest importance, the move towards professionalization noted above distanced the excavator from her/his audience. This dissociation from the community we serve has increased further with recent commercialization, creating mobile excavation companies with no set geographical area of interest. How might we cross that divide? And if commercial excavations are to remain research-driven, who should set that agenda and at what level: local, regional, national, or international?

SEE ALSO: Aerial Photography; Airborne Remote Sensing; Archaeological Fieldwork; Augering; Burial Excavation; Chemical Mapping; Community Heritage; Coring; Cultural

Resources Management; Electrical Resistivity; Experts and Stakeholders; Geomorphological Survey; Gradiometry; Ground-Penetrating Radar; Heritage Ethics; Magnetometry; Marine Excavation; Micromorphology; Nanoarchaeology; Sampling in Environmental Studies; Soil Survey; Total Station

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Terrestrial Lidar

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Traditional methods of site survey for heritage preservationists and archaeologists are often time-consuming and involve the use of subjective techniques such as sketch and field drawings, drawings derived from images, and survey mapping using local systems of reference that lack global coordinates. Documentation of features and objects within a site or structure is also often performed using subjective or time-consuming dimensional recording strategies, including hand-drawn and measured renderings or computer-aided drawings (CAD) that rely on hand measurements, and require physical access to the object or area being documented. Terrestrial lidar survey and laser scanning applications, particularly when integrated with other forms of spatial survey and documentation, offer new potentials for more rapid, robust, accurate, and representational recording of archaeological and heritage phenomena.

Aerial lidar or aerial laser scanning (ALS) is perhaps more broadly applied and understood in the heritage and archaeological sectors than is terrestrial lidar or terrestrial laser scanning (TLS). Several recent exciting applications of ALS, including archaeological prospection of Maya sites in Belize and at the site of Angkor Wat in Cambodia, are producing results that provide broader landscape and spatial coverage capabilities. TLS affords a higher degree of resolution and point density than ALS, and is used in heritage to record phenomena at a closer scale. TLS offers a rapid and highly accurate means of documenting complex archaeological sites and objects in 3D, producing a quantifiable output. Like ALS, TLS is a form of active remote sensing survey that utilizes light pulses and their reflectance to measure distance. TLS data can be used to provide high-resolution terrain and surface details that are representative of the object or environment.

This form of survey is often used in a multisensor approach, with photogrammetry and imaging, global positioning system (GPS) survey, and ALS strategies often performed together.

TLS survey can be performed using static, mobile, or handheld platforms, and can provide a means of acquiring direct measurement across complex or difficult-to-access locales. Tripod-based survey using TLS is used in heritage and archaeological studies to provide highly accurate dimensional recording of sites, features, and objects of interest. Instruments used in the static tripod survey approach range from centimeter accuracy at the long-range landscape scale, to millimeter accuracy, with surveys of built structures and historic resources generally falling in the 1–2 millimeter accuracy tolerance. Instrument types in this range include time-of-flight (TOF) or pulse-based scanners, and phase shift scanners, with differences in the way that distance measurements are resolved based on the way that light is sent out from the instrument. In general terms, phase-based scanners are fast and can acquire data at a rate upwards of a million points per second, but generally do not penetrate as far as a TOF laser. Phase-based scanners can be more accurate, but have limitations on distance, being best suited for documentation out to 300 meters. New technologies are blurring the distance distinctions, with phase and TOF laser scanners now generally able to be used in similar environments out to several hundred meters depending on the instrument, but longer-range ground-based scanning out to kilometers is possible with certain TOF configurations. Preference for work flow and use with integrated surveying strategies are the most common reasons for instrument selection. Choice of TLS equipment also centers on data density requirements, data noise and clarity, ease of use, cost, and instrument weight and size. Trends in scanning instruments have been moving towards smaller, more portable and easy to use options, with lower price points and integrated sensors such as high-resolution cameras, on-board computer interface and touch screens,

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and GPS possibilities. Many of the static or tripod instrument options are able to be adapted to mobile platforms, such as vehicle mounting, and more recently smaller scanners are being utilized with unmanned aerial vehicle (UAV) drone device deployment.

Data generated from both static and mobile applications provide precise X, Y, and Z measurements in dense point clouds that represent the external surface of a structure, terrain, or object, and can also contain information regarding surface reflectivity and color when used with integrated photography and imaging systems. TLS phase shift and TOF instruments are spherical scanners, and can collect measurement data and imagery in 360 degrees horizontally and 300 degrees vertically. Data are acquired rapidly, with survey positions established to allow for movement of the scanner to a prescribed distance and acquiring targeted commonality between scan locations.

Tripod or static survey methods often involve the use of targets or markers that provide reference for precise registration of the data. Artificial references using sphere and target configurations are often specific to the hardware and software choice, and are used as part of a survey kit to provide a means of scan alignment and registration. Alignment can also be obtained based on 3D image matching procedures that examine natural references, such as planes, rectangles, and corner points, but these methods often require more overlap commonality between scans and can be less accurate than using artificial references or assigned coordinates. Target locations can be shot-in using GPS or total station methods, with coordinate control applied to the scan data for higher accuracy and match (Kinney 2017).

Photographs acquired either internal or external to the scanner are used to provide color and texture, allowing for a realistic depiction of the heritage or archaeological phenomenon (Remondino and Campana 2014). Many scanners have on-board cameras that also provide spherical image capture in 360 degrees, allowing for immersive virtual data exploration.

Taking point-based measurements into a surface meshing software allows for solid surface development, producing highly detailed rendered models. Depending on software preference and post-processing pipeline, point cloud or solid

surface models can be used to create measured sections and drawings, and these data derivatives are becoming more automated, with 3D software packages offering valuable applications for architectural and structural engineering specialists in the heritage sector. Visualizations, animations, computer-aided drawings (CAD), and model renders have broader impact value for heritage tourism and interpretation, and are increasingly being shared through global 3D social media platforms, and through the use of embeddable viewers online.

Hand-held and portable laser scanning is generally available for more close range and higher precision needs. These types of scanners include short-range triangulation instruments and projected or structured light instruments. Laser-based scanners capture an object's shape by projecting a laser line or multiple lines onto an object and then detecting the reflection using single or multiple sensors. Using triangulation, the locations of points are determined by forming triangles between them, allowing these scanners to capture a 3D shape accurately (Stylianidis and Remondino 2016). Point cloud areas or patches collected from these scanners can then be merged or stitched manually, or are captured using real-time registration utilizing commonality in the positions recorded (van Dijk et al. 2016). These merged or solid surface data can then be further refined using 3D modeling software. Triangulation scanners are a good choice for archaeological documentation that requires high precision and accuracy for objects ranging in size from hand-held to approximately the size of a car. These types of scanners are less sensitive to lighting conditions and can be more portable and able to scan tough surfaces such as dark or shiny objects. Examples of archaeological applications using triangulation scanners include museum collection documentation, and digitization of sculptures and monuments (Cordova Tello et al. 2016; Doering and Collins 2010; van Dijk et al. 2016).

Structured light scanning instruments are increasingly becoming more widely used in archaeological field methods, but care must be taken for environmental conditions, such as lighting and appropriateness of surface and area that are being recorded. Structured light instruments offer high geometrical accuracy, and are most appropriately used in controlled environmental

settings, such as in museums and laboratory settings (Kersten et al. 2016). Trade-offs with these types of scanners include the size and type of materials that can be captured, and the necessity for control over environmental conditions, such as lighting. Many commercially available structured light and triangulation scanners now come in affordable and highly portable size and weight configurations, with on-board computing integration and options for battery powering, which makes these instruments a reasonable addition to the archaeological digital field kit.

There are numerous examples of successful application of TLS survey methods in the archaeological and heritage sector. These types of tools have been used to record complex terrains, and perform analyses relating to land formation and use processes, such as erosion, and change detection. TOF and phase-based spherical scanners are suited for the examination of landscape and architectural built environments. TLS methods can provide detailed terrain and structural analyses and understanding, with point clouds used to produce digital surface models (DSM), contour maps, 3D CAD, elevations, profiles, volumes, and section details.

TLS is also proving a useful survey strategy in rescue and disaster response scenarios, with examples of rapid, non-contact survey needs in areas where heritage and archaeological sites are imperiled or threatened by natural and cultural change, or activities such as terrorism and war (Greenop and Landorf 2017). TLS surveys in difficult-to-access cave and karst environments are being conducted to map complex features, to conduct pattern and condition assessment, and to perform monitoring for erosion and weathering processes. Geophysical survey techniques in these environments, such as ground-penetrating radar (GPR) survey, can be conducted along with TLS to provide above-surface terrain characteristics that relate to the below-surface anomalies.

TLS, along with other forms of portable structured light and triangulation laser scanning, are also valuable in the digitization of monuments, rock art, and carved surfaces (Doering and Collins 2010). Heritage management, museums, and tourism sectors also benefit from these survey and documentation strategies, with TLS increasingly used along with traditional recording methods such as photography and

measured drawings. New lower-cost scanners and photogrammetric and reality capture tools are being incorporated into the archaeological kit (Davis et al. 2017); however, caution in terms of precision or repeatability of measurements with lower-cost devices and modeling is needed, along with considerations for trueness and accuracy of representation, and resolution.

Other heritage and archaeological applications with TLS survey include recording archaeological context, and in situ human remains, artifacts, and features. These types of applications benefit from the rapid, accurate, and non-contact means of survey, the potential for lessening disturbance of remains and artifacts, and benefiting regulatory and legal requirements such as the Native American Graves Protection and Repatriation Act (NAGPRA).

Conservation techniques and applications are also increasingly using 3D and laser scanning data, with rapid prototyping and 3D printing techniques benefiting from the detailed and representational models that emerge from laser scanning. New opportunities for sharing and broad dissemination of 3D models are being used with heritage objects and artifacts that have been laser-scanned. Online sharing and virtual model representation has the potential to increase collaboration and make archaeology more accessible.

The pace of technological innovation in the area of laser scanning for archaeology and heritage is fast, and with any new approach, guidance and caution is needed. Considerations are needed not only for best practices, but for ethical implications such as copyright, permissions, and distribution practices. Instrument selection and approach includes aspects of cost, portability, technical expertise, and appropriateness of scale. Thought must also be given to object surface characteristics such as shine and reflectivity, which can limit scanning results. Environmental aspects such as intensity of light, and exposure to elements such as dust, cold, or heat can also be critical factors in instrument selection and techniques. Understanding the final purpose for the data to be collected can greatly assist with instrument selection, method, and approach needed. Also critical is the production of data with archival stability, with preference for file types that are neutral and flexible in terms of software and operating system.

SEE ALSO: Airborne Laser Scanning and Lidar; Digital Photogrammetry; GPS (Global Positioning System); Image-Based 3D Modeling; Imaging; Laser Scanning; Lidar Data Visualization and Processing; Photogrammetry and Stereophotogrammetry; Total Station; Three-Dimensional (3D) Printing and Additive Manufacturing; Visualization of Ground-Penetrating Radar Data

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Thermography

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Aerial thermography is a geophysical survey method in which thermal infrared radiation is recorded to show the distribution of temperature across a landscape. In archaeological contexts, anthropogenic features and their surrounding soil matrices often absorb and reradiate heat at different rates, causing features to appear as anomalies in thermographic images. Consequently, these images, called thermograms, may be used as maps which plot the location of subsurface archaeological features.

Archaeologists have been benefiting from the indirect collection of thermal data throughout the last century. The patterns created by unevenly melting snow form a sort of low-tech thermogram of a landscape. If archaeological sites are present, these patches may form regular patterns which trace the location of features. When seen from above, these snow marks can reveal a bird's-eye-view map of buried archaeological sites (see AERIAL PHOTOGRAPHY).

Regrettably, the fleeting phenomenon of snow marks is an unreliable tool for archaeological prospection. They are difficult to predict and appear only when conditions of climate, weather, and lighting align perfectly. Contemporary thermography, or thermal imaging, avoids these obstacles by filming surface temperature in the form of thermal infrared radiation directly with thermal cameras.

Thermal properties of materials

As in other forms of geophysical survey, thermography is used to detect archaeological features by looking for anomalies caused by unique behavior (see ELECTRICAL RESISTIVITY; GROUND-PENETRATING RADAR; and MAGNETOMETRY). The thermal behavior of materials is

determined by four thermodynamic properties: thermal conductivity, heat capacity, thermal inertia, and diffusivity. Most of our current knowledge of how these variables interact and manifest in archaeological contexts is attributable to the work of Périsset and Tabbagh (1981). While most archaeologists will not need complete command of the mathematical formulas they discuss to successfully employ thermography in their research, comprehension of these properties is beneficial in predicting when thermal imaging may be most productive, as well as in interpreting results.

The first thermodynamic property that may affect the behavior of archaeological materials is thermal conductivity. This describes the quantity of heat that a material is able to transport. Subterranean archaeological features will only be detectable via thermography if the soils they are buried in have sufficient thermal conductivity to allow a measurable amount of heat to penetrate to their depth.

The thermal conductivity of soils is dependent upon moisture, organic matter, density, and texture. In dry soil the spaces between particles are filled with low-conducting air, which restricts heat transfer. As moisture content increases, air is replaced with water and overall conductivity improves. Similarly, dense soils have greater contact between particles and higher conductivity than loose or porous soils. However, thermal conductivity decreases as organic matter increases and as soil particle size decreases. As a result, sand has high thermal conductivity, followed by sandy loam, loam, and clay soils.

The second thermodynamic property is heat capacity. Heat capacity does not describe how hot or cold a material can get, but rather how much thermal radiation must be consumed or lost to change the temperature of that material. For example, iron has low heat capacity, meaning it does not require much energy to become hot or cold. Water has high heat capacity, so it must absorb (or lose) a very large amount of thermal radiation before it undergoes a measurable temperature change.

Heat capacity can be described in two ways: specific heat and volumetric specific heat. The

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specific heat of a material is how much heat is necessary to increase the temperature of a unit *mass* of that material by 1 °K. The volumetric specific heat is the amount of heat necessary to increase the temperature of a unit *volume* by 1 °C. The conversion from specific heat to volumetric specific heat is calculated by multiplying the specific heat of a material by its density. In a heterogeneous soil matrix, the volumetric specific heat is the sum of the specific heats of all the soil components multiplied by the bulk density (Stanjek and Faßbinder 1995, 97). For archaeologists, volumetric specific heat is the more useful description of heat capacity as it takes into account both the density and the natural heterogeneity of soils, and because site size is usually described in terms of volume, not mass. However, rarely would an archaeological surveyor need to calculate this property precisely. It is often simpler and just as beneficial to focus instead on the third thermodynamic property.

The third thermodynamic property, thermal inertia, describes a material's resistance to changes in temperature. Thermal inertia I is represented by the equation

$$I = \sqrt{k \cdot C_v}$$

where C_v is volumetric specific heat and k is thermal conductivity. From this equation it can be seen that high thermal conductivity and/or high volumetric specific heat leads to high thermal inertia. In practice, the range of values for thermal conductivity is fairly small compared with the range of possible volumetric specific heat values, so thermal inertia is primarily determined by the heat capacity. A material with high heat capacity usually has high thermal inertia and vice versa. Due to its high heat capacity, water has high thermal inertia and is resistant to temperature changes. Because of the close association between these two properties and the relative ease with which thermal inertia is observed in the field, it is a very convenient proxy for heat capacity.

Possessing knowledge of the thermal inertias of the types of materials likely to be found in an archaeological site can be useful for estimating the potential strength of anomalies and in analyzing results. Like thermal conductivity, heat capacity and thermal inertia are predominantly affected by density and moisture content. Less dense or

porous soils tend to have low heat capacity and low thermal inertia. As density and/or moisture content increases, heat capacity and thermal inertia will increase (Stanjek and Faßbinder 1995, 97). Therefore, dry porous soils like sand will respond to temperature changes quickly, while moist, dense soils resist temperature change. Damp features such as filled ditches or wood objects will also resist temperature change, but low thermal inertia materials like metals will undergo more rapid and extreme changes in temperature.

The fourth thermodynamic property, diffusivity, describes how easily heat is conducted through a material. While thermal conductivity describes the quantity of heat that can be transported through a material, thermal diffusivity describes the rate at which temperature change occurs. As thermal radiation passes through a material, some will be absorbed, depending on that material's heat capacity. A material with low heat capacity will have high diffusivity, meaning that most heat travels through it quickly without being absorbed. In an archaeological site with high diffusivity soil, subterranean features will be exposed to thermal radiation more quickly, which will then allow them to experience temperature changes at rates dependent on their own thermodynamic properties, rather than being insulated and limited by the properties of the surrounding soil matrix.

Mathematically, diffusivity is the ratio of thermal conductivity to volumetric specific heat. It can be represented by the equation

$$\Gamma = k/C_v$$

where Γ is diffusivity, k is conductivity, and C_v is volumetric specific heat. The higher the thermal conductivity is relative to the heat capacity of a material, the higher the diffusivity will be. Finally, the relationships between all four thermodynamic properties can be described when the equation for thermal inertia I from above is rewritten as follows:

$$I = \sqrt{k \cdot C_v} = k/\sqrt{\Gamma}$$

Périsset and Tabbagh (1981) created several experiments to study the interaction of these thermodynamic properties. They constructed artificial archaeological features and designed a software program to analyze the thermal behavior of a feature embedded in a subsoil and then

covered with a superficial layer of a second soil type. From these experiments they were able to observe how the layers of soil around an archaeological feature will affect its thermal signature:

- As the superficial layer increases in thickness or decreases in diffusivity, thermal anomalies created by the feature will attenuate and their appearance will be delayed.
- As the superficial layer increases in conductivity, the thermal anomalies will attenuate, but will not be delayed.
- The superficial layer will have no effect upon the relative temperature of a thermal anomaly. Whether it appears as relatively warm or cold depends solely upon the properties of the feature and the surrounding subsoil.
- As thermal conductivity and diffusivity of the feature increase, thermal anomalies may be weaker as more heat is distributed into the surrounding soil and less is retained by the feature itself.
- Features located within low conductivity and low diffusivity subsoil will have the strongest thermal signatures.
- The potential strength of a thermal anomaly is determined by the thermal inertias of the feature and the subsoil. The greater the difference in thermal inertia, the greater the anomaly (Périsset and Tabbagh 1981).

Other characteristics of the surface layer can affect the outcome of a thermal survey. Heterogeneous surface soils are created by human activities, natural variations in bedrock and hydrology, and the presence of archaeological material. These inclusions can be helpful if they reflect the presence of archaeological features, such as mudbrick fragments brought to the surface by plowing. Conversely, they may create thermal noise which masks subsurface features. Variations in surface topography result in uneven surface exposure to thermal infrared radiation. If topography reflects subsurface features, such as a slight ridge over a buried wall, this impact may be positive. However, surface topography can also obscure anthropogenic thermal anomalies if it is unrelated to the presence of subterranean features (Scollar et al. 1990, 601).

Thermal cameras

Thermal infrared radiation has been traditionally recorded via satellites and scanning radiometers. However, thermal infrared satellite data have extremely low resolution (100 m in the case of Landsat 8), which is entirely unsuitable to most archaeological investigations (see SATELLITE HYPERSPECTRAL AND MULTISPECTRAL IMAGING). The scanning radiometer was an expensive, airplane-mounted system which required intensive image correction, georectification, and data processing. Predictably, aerial thermography was not a practical surveying method for most archaeologists. Only in the early twenty-first century has the deployment of aerial thermography become a feasible prospecting method for archaeologists, due to the concurrent development of compact thermal video cameras and drones (see DRONES).

The quality of data recorded by a thermal camera is determined by four types of resolution: temperature, spectral, radiometric, and spatial. Temperature resolution is the temperature increment the camera is capable of detecting. Spectral resolution describes which electromagnetic wavelengths are recorded. Thermal infrared radiation occupies the ranges 3–5 μm and 8–15 μm on the electromagnetic spectrum. Many thermal cameras record only within the 8- to 15- μm range. Radiometric resolution refers to the way data are encoded. Thermal cameras that record at 8-bit resolution are capable of representing temperatures with a maximum 256 different colors. Finally, spatial resolution refers to the real physical area each pixel represents and depends on the camera's proximity to the ground. In all cases, higher resolution is capable of offering more information; however, too much detail can become noisy and difficult to interpret.

Thermal video cameras usually record grayscale images, with black cells assigned to the coldest areas and white cells for the warmest. This is a relative scale that depends on the range of temperatures within each frame; that is to say, most thermal cameras do not consistently assign the same gray values to the same temperatures. This can make comparing thermograms problematic, as the same range of colors may be used to represent completely different temperature ranges.

Some cameras autocalibrate while recording, so temperature representation may not even be consistent frame to frame. The ideal thermal camera can be pre-calibrated to ensure consistent temperature representation. If such a camera is not available, this issue can be minimized by establishing ground control points with known temperatures to use as reference points for manually calibrating or resampling the data during processing.

Surveying

In aerial thermography, thermal cameras can be carried by drones, kites, or balloons, or mounted on a fixed object at high elevation. Data can be collected with a single overview shot that records the changing temperature of a specific area over time, or the data can be collected in transects to cover large areas while maintaining high spatial resolution. However, the surveyor must keep in mind that temperatures will change over time, so surveys should be kept short to maintain consistency. Ground control points must be placed around the survey area to allow georectification. Simple tin baking dishes staked to the ground will show up brightly as very cold areas at night, or highly reflective warm areas during the day. Plastic or wood ground control points are unlikely to be visible in the thermograms and are not recommended.

Archaeological features are not guaranteed to always produce visible thermal signatures even when they have distinct thermal properties. Radiation reflected from the surface or ground cover may obscure subsurface anthropogenic anomalies. Most thermographers choose to collect data at night to avoid this complication. Another obstacle can arise when a long stretch of stable weather allows temperatures of subsurface materials to equalize. Thermal surveys must be conducted while the temperatures of materials are still adjusting and differences are at their maximum.

Thermal surveys are most often successful when conducted after a shift in heat flux direction. The heat flux value $\emptyset$ denotes both the rate and direction of travel of heat from one material to another and is defined by Fourier's law: $\emptyset = -k\nabla T$. Essentially, a material with positive

heat flux is absorbing heat, while negative heat flux indicates that the material is losing heat. The larger the heat flux value (in either the positive or negative direction), the faster the change is occurring.

Deeply buried anthropogenic anomalies will be most visible after a shift in slow, transient heat flux. If a week of stable warm weather which has allowed all materials to reach thermal equilibrium is followed by a cold snap, materials with low thermal inertia will cool quickly, while those with high thermal inertia will remain warm. Thermograms collected during this transition period will reveal the strongest thermal anomalies (Périsset and Tabbagh 1981, 170–171).

Diurnal heat flux can also be revealing. Near-surface features or surface inclusions that reflect buried features will experience daily temperature variations, and so can stand out as anomalies after daily heat flux shifts. In contrast, seasonal heat flux changes are less productive. While seasonal temperature changes have deep penetration, other surface changes throughout the year caused by vegetation growth, humidity, and human activity create so much noise that most anomalies are obscured (Scollar et al. 1990, 597–598).

Data processing

After thermal video data are collected, surveyors extract still-frame thermograms to analyze individually or mosaic into a single image. Thermograms are stored as raster files wherein each pixel or cell represents an area and the average temperature in that area. These data can be imported to any geographic information system (GIS) program for further processing. It can be georeferenced to real-world coordinates and then compared with photographs, maps, or other geophysical data to aid in interpretation. The thermograms may also be filtered, resampled, and otherwise manipulated to highlight subtle thermal anomalies.

Bellerby, Noel, and Branigan (1990) tested three methods for filtering out surface noise created by diurnal variation, irregular topography, and soil inhomogeneities. They collected multiple temperature readings at each point in their survey

grid and at a base station. They used the first and last base station reading to interpolate a linear function representing the overall change in temperature over time. They then subtracted it from the total set of base station data. Finally, they converted the data into a Fourier series which represents the waveform pattern of temperature change over time and subtracted from the site grid data. Using this method to reduce thermal noise allowed them to isolate deep features from surface anomalies.

Occasionally an anthropogenic feature may not create a sufficiently distinct thermal anomaly to be visually identified in a single thermogram. In this case, it may be possible to locate the feature by identifying an associated temporal anomaly. This can be done by comparing multiple sequential thermograms of a single area. If a particular cluster of cells has significantly more or less temperature variance than its neighbors, this would indicate the presence of a material with higher or lower thermal inertia—that is, more resistant or more susceptible to temperature changes (Danese et al. 2010). This analysis can be done by calculating the standard deviation of corresponding cells across several thermograms using raster math. In the resulting raster, each cell would represent the temperature variance in that area.

Future directions

Aerial thermography is becoming increasingly popular as thermal cameras and drones become more accessible. Recent projects have demonstrated that aerial thermography is a highly productive survey methodology in arid areas such as the American Southwest and the Near East (see Further Reading). Ongoing research will inevitably lead to refinement in our understanding of survey timing based on seasonal and weather patterns as well as developments in data processing methodology. As the

technology and our ability to interpret the data improve, the suitability of aerial thermography will be expanded to include other regions.

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Total Station

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Total stations are electronic surveying instruments that incorporate electronic distance measurement (EDM) to allow measurement of three-dimensional locations with a high degree of accuracy and precision (Figure 1). They are closely related to theodolites, electronic or otherwise, that do not have in-built abilities to precisely measure target distance from the instrument. Total stations measure horizontal and vertical angles to impressively low errors of about 0.00028–0.00139 degrees, sufficient to allow locating exact points up to a few kilometers away from the instrument. The EDM component of total stations emits infrared laser pulses that are reflected back to the instrument from the target of measurement. The amount of time elapsed (time-of-flight) in this rebound is used to precisely determine the distance between the instrument and the target. The resulting spherical coordinates (horizontal and vertical angles, and the measured radial distance out from the total station) that unambiguously determine the position of the target can be trigonometrically transformed into cartesian coordinates, typically measures of easting, northing, and height in relation to either the total station or an absolute datum. The electronics of the total station usually do all calculations, to deliver to the user the target's location in such XYZ site or global coordinates (Rick 1996).

Physically, a total station consists of a telescope capable of sighting the target, a keyboard to input the specifications of the user (coordinates, program commands, target codes, etc.), a display to deliver visual/numeric information to the user, the EDM (now usually incorporated within the rotating head containing the telescope), and a leveling base that usually sits on top of a strong tripod. In use, the total station is placed

above a known point or datum—or related to a series of known points—to fix the instrument's current position within a coordinate grid, and the directional orientation in that plane (e.g., the direction of north) and the instrument's height above that plane are determined. Once this setup is verified, the total station can sight, measure, and record target points within coordinate space at high levels of accuracy and precision. In practice, artifact locations, dimensions of architecture, site topography, and any other spatial features of a site can be recorded, usually to internal memory or a variety of memory devices of varied capacity. Two principal types of targets are used. Older instruments depend on targeting a mirror-like retroprism reflector mounted on a vertical, usually manually held and leveled rod which returns the laser pulses. More recent instruments add the possibility of reflectorless function, in which the laser pulses are reflected off the actual object of archaeological or topographic interest. In general, reflectorless function has a more limited measuring distance (originally under 100 m, but now closing in on the practical single reflector limitation of around 1 km), but offers the possibility of measuring locations in which a reflector cannot be easily placed, and also faster single-user operation.

Most total stations incorporate a number of programs that are useful in archaeology. Important among these is the “setting out” or “stake out” routine in which the coordinates of a point are entered, allowing the instrument to aid the user in finding the point, by indicating either the radial line and distance from the total station where the point should lie, or the necessary displacement north–south or east–west from a given position. This is particularly advantageous for laying out excavation units on highly irregular or sloping surfaces, where determining leveled horizontal distances is difficult with lesser instruments or by hand. Another useful program is free-station, or resection, in which the instrument's setup location is determined by measuring a series of known points, and calculating a least-squares



Figure 1 Total station in use at Chavin de Huantar, Peru.

Source: Photo by author.

solution, complete with error terms for distances and angles to each point. This allows great freedom in setup locations, and assures that any new instrument location is corroborated by a series of reliable points.

Obtaining or renting total stations may represent a significant expenditure for modest projects, and these sensitive instruments must be maintained conscientiously to be reliable. Cost can range from under US \$5,000 to well over \$30,000, depending on accuracy and features. Accuracy of course decreases at greater measurement distance from the instrument due to the diverging radial lines of potential readings. Most instruments range from 1 to 5 seconds of angular accuracy, meaning that at a typical long measurement distance of 100 m, expectable intrinsic errors of around 1–3 mm can be expected. No common spatial point location method currently competes with this accuracy, in the range of 0.001–0.003 percent error over a given distance. Advanced total stations have robotic features for tracking a reflector automatically, allowing a single operator with radio control to command point registration

while moving a reflective target to the points of interest (Kvamme, Ernenwein, and Markussen 2006). There is also a certain degree of unattended operation, in which advanced total stations can take reflectorless measurements within a defined field of view on an automatic basis.

The use of total stations articulates closely with other spatial technologies in archaeology (see FIELD SURVEY). Global positioning system (GPS) instruments that determine target locations based on signals from satellites can provide worldwide coordinates, useful to position more local total station measurements (see GPS (GLOBAL POSITIONING SYSTEM)). Some total stations include GPS measure capabilities. Laser scanners and photogrammetry quickly gather masses of three-dimensional data at the inter-site level, but require accurate base measurements to fix their collected data within the site's context (see LASER SCANNING and PHOTOGRAMMETRY AND STEREOPHOTOGRAMMETRY). Total stations are the most common option for this, because their millimeter accuracy is difficult to achieve by other methods, and because they do not require the satellite lines-of-sight of GPS instruments. At the same time, total stations require line-of-sight from the instrument to either the reflector or object target, sometimes an inconvenience in topographically or architecturally complex situations. Total stations have traditionally been somewhat difficult to comprehend and use, but increasingly well-programmed software, together with relatively large display screens allows a more user-friendly interaction between operator and device. Overall, most substantial excavation or mapping projects will benefit greatly from the competent use of total stations.

SEE ALSO: Image-Based 3D Modeling;
Terrestrial Lidar

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Underwater Three-Dimensional Laser Imaging

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Three-dimensional (3D) laser imaging systems are devices that emit a laser beam which shines on an object located at meters of distance and that record a portion of the laser light reflected back by the object's surface. The device processes the received signal and generates a 3D digital model of the object for visualization on a display, where each point of the object's surface is assigned a set of spatial coordinates in a relative reference frame.

The application of 3D laser imaging systems in archaeology and heritage on emerged land has been steadily growing since the 2000s, mainly in view of the considerable progress in optoelectronic technology. Successful applications have been demonstrated for operations at tens of meters of distance from the targeted object (range) and with submillimeter spatial resolution (accuracy).

Transposition of 3D laser imaging technology to the underwater environment is not straightforward, however, and recording 3D models of subsea archaeological sites is of key importance to make available to experts a valuable set of data for drawing documents, cataloguing, and planning preservation and restoration interventions.

The presence of a column of water between the laser-based device and the target and the demand to operate at depth introduce severe scientific and technological challenges. Many of them have been successfully addressed in recent years and this is why underwater 3D laser imaging technique is slowly but steadily bridging the gap with respect to its homologous counterpart on emerged land.

To begin with, water is a dissipative transmission channel for laser light, with detrimental

effects on the range and accuracy of underwater 3D laser imaging systems. In fact, water attenuates laser light as it propagates through the aqueous medium and with an exponential law. If I_0 is the laser beam intensity as emitted by the underwater 3D laser imaging system, the intensity I_z at a distance z in the aqueous medium is given by:

$$I_z = I_0 e^{-kz}$$

where k is the attenuation coefficient that is the sum of two terms: k_a , the absorption coefficient, and k_s , the scattering coefficient. Both coefficients have the dimension of the inverse of a length and show a pronounced dependence on the laser beam wavelength λ . Absorption is the process by which water removes a fraction of the optical energy from the laser beam, ultimately converting it into heat. With the scattering process, water redistributes part of the optical energy of the laser beam into spatial directions other than that of the laser beam propagation.

In the clearest oceanic waters, k_a dominates with respect to k_s and the minimum value for k is nearly 0.02 m^{-1} at $\lambda \sim 410 \text{ nm}$. As water turbidity increases, k_s becomes the prevalent contribution and the values of k range from 0.1 m^{-1} for least transparent oceanic waters to 1.2 m^{-1} for coastal areas at $\lambda \sim 530 \text{ nm}$.

This means that in the most transparent oceanic waters, 3D laser imaging systems based on laser-emitting radiation in the 405- to 450-nm region are best suited, with potentiality of operation up to 10 m range.

On the other hand, in the least transparent oceanic waters and in coastal zones, only short-range operations are possible (up to 3 m), using systems based on lasers emitting light in the green region of the electromagnetic spectrum.

The necessity to operate at depth introduces other factors of merit for an underwater 3D laser imaging system beyond range and accuracy. Such factors are related to the technological challenge of marinizing the system and making it qualified to operate in real underwater scenarios. Among them, *size* and *weight* are the most important.

In fact, an underwater 3D laser imaging system could be operated in two ways: deployed on tripods on the seabed, offering a stable platform; or installed onboard a remotely operated vehicle (ROV). The first case is pursuable only in the relatively shallow waters accessible to divers who incrementally reposition the tripod in order to cover the entire structure to be visualized with the field of view of the sensor. When mounted on an ROV the sensor must be stably fixed to it and accommodated together with other sensors like cameras, sonars, robotic arms, and samplers. In this case, the 3D laser imaging system is hardwired through the ROV tether to the operator controlling the vehicle from a ship above the inspected site. Mainly for ROV operations, another key performance indicator is the *maximum depth of operation*. The housing of the device must be qualified to operate at the depth of interest for the specific applications, which in some cases are conducted in deep waters. Common to the diver-assisted and ROV operation is the issue of the *vibration and shock resistance* of the sensor, which determines its capacity to withstand the hard operative conditions found in underwater environments. For instance, during survey missions with ROVs, acceleration up to 4g is routinely achieved. Finally, the device must be *robust to thermal cycling* due to the thermal gradient suffered by the sensor during the initial deployment at sea level and further operations in proximity of the seabed.

Laser sensors for 3D imaging in underwater environments share a basic scheme with their homologs used on emerged land: a launching stage emitting the laser light that illuminates the target and a receiving stage detecting the signal to be processed for generating the 3D model. The laser can be a spatially collimated beam hitting the target surface at a single point, a laser stripe projecting a line onto it, or an expanded fan illuminating the whole target surface in one shot. The range information is encoded in a measurable parameter of the fraction of the laser light reflected back by the target and recorded by the receiving stage.

In *triangulation systems* the range information is encoded in the spatial position on the receiving sensor of the optical signal recorded. In these systems, the launching stage and the receiving stage are separated by a distance x (baseline), and

if d is the range to measure, the error δd in range estimation (accuracy) scales as d^2/x . This explains why underwater 3D laser imaging systems based on the triangulation technique have a limited operative range of a few meters. The possibility to reduce δd by adopting a large baseline is pursuable, but at the expense of the device's size and field of view. Underwater triangulation systems are based on continuous lasers and adopt a laser stripe as the illuminating beam and a 2D imaging array as the receiver. This allows reducing the 3D model acquisition time by sweeping the laser stripe on the target surface. Recently, a commercial system based on triangulation and with a baseline $x = 50$ cm has been successfully used for recording the accurate 3D models of a shipwreck in Thunder Bay Marine Sanctuary, the United States (2G Robotics 2016) and with an operative range $d \sim 5$ m. The device was mounted on a tripod and laid on the lake bed for the 3D model acquisition.

Another class of underwater 3D laser imaging system is based on time-encoding methods. This means that the range information d is retrieved after having measured a temporal parameter of the laser beam. Among them, the most advanced devices are those operating with the *time-of-flight* method. These systems are based on a laser emitting pulses in the picosecond or nanosecond time regime and spatially collimated. The range information is encoded in the round-trip time of the laser pulse traveling from the launching stage to the receiving stage after having been reflected back by the target surface. If $t = 0$ is set as the instant at which the laser pulse is emitted at the launching stage and Δt is the measured round-trip time, the range d of the point on the target surface sampled by the laser beam is given by

$$d = (c\Delta t/2n)$$

where c is the velocity of light in the vacuum and n is the index of refraction of the aqueous medium.

In order to measure Δt with high precision and to achieve submillimeter values for δd it would be necessary to use pulses in the picoseconds time regime, whose generation requires bulky laser sources. Nevertheless, a better trade-off between range accuracy and the sensor's size and weight is achieved with laser pulses in the nanosecond

time regime. In fact, this allows using less bulky laser sources, while submillimeter range accuracy is ensured by the adoption of more sophisticated detection and data processing methods. One of the advantages of the time-of-flight system is the possibility to drastically cut the optical noise produced by the fraction of the laser beam that is backscattered by the aqueous medium and that falls into the receiver field of view with appropriate time-discriminating detecting methods. For typical oceanic waters with $k \sim 0.1 \text{ m}^{-1}$, underwater 3D laser imaging systems based on the time-of-flight method can reach a range accuracy of 30 mm at 10 m of range. Successful applications of these kinds of devices have been demonstrated both for operation onboard ROVs during several survey missions for the offshore oil and gas industry and in static operation once deployed on a tripod in the turbid water of a lake for 3D model acquisition of shipwrecks (3D at Depth 2016).

Always based on a time-encoding method are the underwater 3D laser imaging systems using intensity-modulated laser beams and working with the *MODEM* (MODulation/DEModulation) *technique*. These devices are essentially phase-shift sensors that measure the phase delay $\Delta\phi$ that the intensity of a laser beam modulated at a frequency f_m acquires during the path from the launching to the receiving stage. If d is the range of the point on the target surface sampled by the laser beam, the following relation holds:

$$\Delta\phi = 4\pi n d f_m / c$$

The pioneering work of Mullen et al. (1995) demonstrated that the intensity-modulated component of the laser intensity backscattered by the aqueous medium has a low-pass filter dependence on f_m . This means that for operation at modulation frequencies f_m greater than a cut-off value f_{co} , the receiving stage is less sensitive to the backscattered laser radiation. The cut-off frequency f_{co} is inversely proportional to the attenuation coefficient k and for typical oceanic waters has a value around 100 MHz that is easily obtainable with current laser technology. Range accuracies of the order of 5 mm have been attained with a prototype sensor based on an

intensity-modulated laser and in turbid water with $k = 0.3 \text{ m}^{-1}$ and at a range of nearly 3 m (De Dominicis et al. 2010).

The visual rendering of 3D models recorded with underwater 3D laser imaging systems is provided in a scale of grays according to the level of reflectivity of the target surface to the wavelength λ of the laser beam mounted on the sensor. The potential to generate colored 3D models of submerged targets has been demonstrated in a laboratory experiment using an intensity-modulated system where the output of three different lasers with wavelengths in the red, green, and blue regions was mixed to generate a single laser beam that measured the target surface reflectance at the three wavelengths.

SEE ALSO: Image-Based 3D Modeling; Laser Scanning; Terrestrial Lidar

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Archaeological Sciences

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Archaeological sciences and *archaeological science* are generic terms commonly used to refer to the many subdisciplines that involve the application of science, technology, engineering and mathematical methods in archaeology. Most frequently defined by their methods rather than by specific aims or study areas, archaeological sciences cover the engagement of a wide range of disciplines such as physics, chemistry, biology, genetics, computing, or medicine to the study of both organic and inorganic archaeological remains, as well as associated sediments or contextual information such as their date or spatial location.

Most archaeological sciences generate primary data about aspects of the composition and microstructure of archaeological samples and reference materials, which in turn allow inferences about subsistence (e.g. through bone isotopes that inform about diet (see DIET AND CARBON ISOTOPES and DIET AND NITROGEN ISOTOPES)), or organic residue analyses in cooking pots (see ORGANIC RESIDUE ANALYSIS), health (e.g., identifying paleopathology (see PALEOPATHOLOGY)), environment (e.g., through pollen identification (see PALYNOLOGY) or zooarchaeological analysis (see ZOOARCHAEOLOGY)), technology (e.g., through metallographic analyses (see METALLOGRAPHY) or ceramic petrography (see PETROGRAPHY AND CERAMICS)), trade (e.g., through geochemical provenance studies (see CHERT, SILEX, AND OBSIDIAN SOURCING)), migration (e.g. through ancient DNA (see DNA: NEXT GENERATION SEQUENCING and DNA: MITOCHONDRIAL)), and other aspects of past lifeways. In addition, archaeological sciences are useful in the identification and survey of archaeological sites (e.g., in remote sensing (see AIRBORNE REMOTE SENSING)), conservation, documentation, and heritage management. Computing and mathematics are sciences often used for the processing

and analysis of primary data (see STATISTICS IN ARCHAEOLOGY), as well as to develop predictive models (see PREDICTIVE MODELING).

It is important to differentiate between *archaeological science* on the one hand, and *scientific archaeology* on the other. Advocates of scientific archaeology predicate the conviction that archaeology should model its methods of inquiry and inference upon those of the natural sciences, irrespective of whether the strategies employed to generate the data are borrowed from advanced science and technology or not. For example, scientific archaeologists often try to falsify hypotheses using archaeological evidence, and apply theories from evolutionary biology to generalize about past cultural behavior. Conversely, archaeological science refers to the development and application in archaeology of techniques and concepts drawn from the natural sciences and engineering, without exclusive reference to any theoretical persuasion. As such, an archaeological project may be framed in postpositivist and relativist theory, and hence negate the possibility of offering any objective facts or generalizations about the past, but still incorporate data obtained with scientific instruments.

Archaeometry (see ARCHAEOOMETRY) is often used as a synonym of archaeological science, although the former term tends to be restricted to the study of sites and inorganic materials rather than biogenic materials. Another relevant term is *heritage science*, which is defined as encompassing “all technological and scientific work that can benefit the heritage sector, whether through improved management decisions, enhanced understanding of significance and cultural value, or increased public engagement” (Williams et al. 2013, 7). Even though some claim that archaeological science is a subdiscipline within heritage science, in practice both fields can share methods but tend to be very different in their aims, scope, and study objects: While archaeological sciences are mostly concerned with making inferences and answering questions about past societies, heritage science tends to be more concerned with the preservation, management, and public

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use of individual heritage items in the present. There are, however, many synergies and overlaps among all of these fields, and sometimes the term employed by a particular researcher or team may respond more to academic traditions or branding than to real distinctions.

Natural scientists applied scientific reasoning to infer the relative ages of some archaeological sites from the late-seventeenth century, some 200 years before the emergence of archaeology as a discipline. By the early twentieth century, pioneer geoarchaeologists, dendrochronologists, zooarchaeologists, and archaeological palynologists sought close cooperation with archaeologists, often doing joint fieldwork with them. Numerous scientists also contributed occasional studies of archaeological materials such as ceramics or metals, though many of these were published as unintegrated appendices. By the 1960s, laboratory-based chemical, provenance, and dating studies were widespread in Europe and America, partly thanks to a renewed optimism about the potential of science in archaeology, and to concerted efforts to ring-fence and fund archaeological science projects (Killick and Young 1997). However, inflated expectations and problems of cross-disciplinary communication led to some frustration and failed efforts, with scientific data often devoid of archaeological interpretation or significance, and not incorporated in core archaeological narratives. The problem was often blamed on the reluctance of scientists to engage with archaeological concerns, although many archaeologists were also guilty of failing to learn about the potentials and problems of science and technology so that they could make more informed requests (Olin 1982). These disagreements led to a backlash against what was perceived by some as an intromission of scientists in archaeology. The retreat was fueled by a growing influence of postmodern relativistic theories in the archaeology of the 1980s and 1990s, which seemed incompatible with the claimed objectivity of science (De Atley and Bishop 1991; Jones 2002). Since 2000, archaeology and science have been increasingly integrated, and the majority of the most significant research topics and findings in archaeology have input from the sciences in both their conception and implementation. This is in large part due to the growing institutionalization of training in

archaeological science, with university degrees that are explicitly concerned with both archaeology and science, and which typically involve staff from different backgrounds and/or departments. As a result of this process, there is a generation of graduates with interdisciplinary training that are ideally suited to facilitate synergies (Martínón-Torres and Killick 2015; Pollard and Bray 2007).

While some archaeologists still see the sciences as a subservient partner whose only role is to produce data, interdisciplinary archaeological scientists have made countless contributions to archaeological research agendas, theories, and models, often driving major developments in the discipline. For example, a surge of research on ancient models of trade and exchange in the 1980s was encouraged by the availability of geochemical provenance studies, which allowed linking artifacts to their source. Discussion of diffusionism versus independent development of multiple phenomena was initially stimulated by developments in dating techniques and, more recently, by high-resolution characterization of technological traditions that can inform about modes of knowledge transmission. Comparative approaches to plant and animal domestication, their pace and cultural significance are led by better sampling strategies, improved microscopy and, increasingly, DNA and statistical reanalysis of legacy radiocarbon dates. It is generally accepted that human evolution can only be understood by drawing on theories and data from science-based anthropology and biology. Core archaeological subjects of clear relevance in the contemporary world, such as agency and identity, are best informed by the combination of genetic, geographic, and cultural data enabled by the archaeological sciences (Martínón-Torres and Killick 2015).

This picture is applicable, to different extents, to the academic and institutional environment in the United Kingdom and United States, in addition to some universities and research centers in Belgium, France, Germany, Italy, Scandinavia, Spain, Israel, South Africa, China and Japan (Killick 2008). In these contexts, attempting to demarcate archaeological science as a branch separate from mainstream archaeology is becoming increasingly irrelevant, since very few would deny that archaeology, like any other academic

discipline, only realizes its full potential when empowered by science. However, the growth of archaeological science is geographically uneven, with many developing countries lagging behind because of difficulties in access to instrumental facilities and relevant training. As such, the development of balanced international partnerships has been identified as one of the major challenges for archaeological sciences in the medium term (Killick 2015). Another major hindrance for the development of archaeological science in some countries has been the reluctance by some governments to allow invasive sampling of heritage objects and/or the export of samples to countries with suitable laboratories. Even though portable and noninvasive analytical techniques have made major strides to overcome these problems, some fundamental techniques still require samples. Most archaeologists favor negotiated decisions that consider the uniqueness of the objects and their heritage value but also the enhanced information and public interest obtained through scientific analyses.

The interdisciplinary collaboration between natural sciences and archaeology has also led to an increased acceptance of the protocols of science as benchmarks for the quality of archaeological research, particularly as regards rigorous data acquisition, reproducibility, and curation that may facilitate validation and reanalysis. The impact of archaeological theories and inferences in the sciences has been more limited, however, and this is another area with great potential for future developments: While archaeology has contributed to reformulations in ecology, including key input to current discussion of the Anthropocene and the management of climate change, scientists are yet to take significant notice of archaeological lessons in other crucial arenas. These arenas include, among others, a time-deep understanding of the contexts that trigger creativity and innovation, the development of productive and socially responsible forms of public engagement, and the use of flexible research frameworks that take advantage of science but accept more methods than the deductive-nomological prescription.

SEE ALSO: Heritage Ethics; Philosophy of Science; Scientific Practice

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Archaeology

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“Archaeology is an undisciplined empirical discipline. A discipline lacking a scheme of systematic and ordered study based upon declared and clearly defined models and rules of procedures” (David L. Clarke 1968: xiii).

Archaeology as an academic discipline is firstly a body of excavation techniques used in the recovery of artifacts and biofacts, human and animal bones; overlaying this is the body of theoretical constructs developed to study and understand, in a social and historical perspective, the organization of human societies through the material evidence brought to light by the archaeologists' tools.

Actually, after an initial stage marked by an antiquarian approach firstly appearing in the Roman world (e.g., the astonishing collection of Greek Hellenistic statues assembled by the Roman Emperor Tiberius at Sperlonga cave), a more structured interest in Greek and Roman art works and culture emerged in the Renaissance period. Following this, a new approach to ancient materials was developed from the mid-eighteenth and early nineteenth century by the scientific method which denotes the Age of Enlightenment, with the publication of the *“Encyclopédie, ou Dictionnaire Raisonné des Sciences, des Arts et des Métiers,”* and Positivism, from Claude Henri de Saint-Simon (1760–1825) to Auguste Comte (1798–1857). This was characterized by systematic data collection and ordering. The discipline at the same time went through a period of diversification into different branches including Prehistoric archaeology, Classical or Historical archaeology, Egyptology, Assyriology, North, Central and South American archaeology.

By the mid-nineteenth century, archaeology had moved towards a cultural–historical approach to explain human origins and cultural change, following the advent of Darwinian evolutionary theory and to reflect new achievements in biological and geological sciences. A new wave of archaeological excavations started and continued during the first half of the twentieth century in the Near and Middle East, as well in Europe, Egypt, and the Americas, with the first interdisciplinary projects like the Carnegie Institution Anau excavations in the Turkmenistan piedmont (Pumpelly 1908).

In the 1950s the discipline experienced what is known as the radiocarbon revolution which provided archaeology with an absolute dating (see DATING IN ARCHAEOLOGY) instrument to construct cultural chronologies. This was later followed by other methods such as uranium–thorium (see URANIUM-SERIES), optically stimulated luminescence (see OPTICALLY STIMULATED LUMINESCENCE), archaeomagnetism (see ARCHAEOMAGNETISM), amino acid racemization, bone-nitrogen, potassium–argon, obsidian hydration (see OBSIDIAN HYDRATION DATING) among others. A few years later a broader and more inclusive approach to archaeology as an anthropological discipline was inaugurated by the well-known North American and British movement of the New or Processual Archaeology. At the beginning, the movement was characterized by a search for general laws moving from description towards an explanation of human cultures and cultural change all along the sequence from the Palaeolithic up to the present. The movement also focused on new branches of the discipline, such as ethnoarchaeology (see ETHNOARCHAEOLOGY). The New Archaeology movement is usually considered as a turning point (or a revolution) in archaeological practice and an elaboration of theoretical constructs pointing to the explanation of cultural change and its interconnection with climatic and environmental changes (Trigger 2006).

An important contribution to the new directions undertaken by the archaeological discipline

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was offered by the advancement of the scientific techniques and methodologies in the material sciences as applied to archaeological materials (see SUBSTANCES AND MATERIALS and ARCHAEOLOGICAL SCIENCES). Beginning with particular studies which usually appeared as appendices in archaeological excavation reports, the contribution of the physical sciences to archaeology started to provide more focused and expanded instruments to nuance explanations of cultural evolution, to environmental and climatic fluctuations, and to material production technologies (e.g., Heizer and Cook 1960; Pyddoke 1963).

Critiques of the New or Processual Archaeology have been advanced on occasion by proponents of a Postprocessual or Contextual archaeology and the more extremist aspects of the movement have now been at least partly abandoned, even by its leading proponents. The new movement was characterized by a rejection of positivism (see POSITIVISM) in favor of relativism owing a debt to the French Marxism and structural anthropology. However its most important achievements have been recently reconsidered and accepted by processual archaeologists.

The original search for general or covering-laws, later translated into an attempt to produce a paradigmatic theory in archaeology (see PHILOSOPHY OF SCIENCE), has largely been abandoned or, at least, deeply questioned due to the basic ontological and epistemological fallacies of both the Processual and Postprocessual thinking (see Wallace 2011). A more pluralistic approach has evolved in the last 20 years, producing strands of theories which attempt to explain human evolution, cultural adaptation and change, diversity and multiplicity, as well as identifying processes shaping the materiality of societies. Among the new trends that, apart from the usual emphasis placed upon them by their proponents, can be considered as part of a unique interpretive toolkit, we can mention agency theory (see MATERIAL AGENCY), social brain hypothesis, evolutionary theory (see EVOLUTIONARY THEORIES), human niche-construction theory, entanglement theory (see MATERIAL ENTANGLEMENT), resilience theory, cultural transmission theory, behavioral theory (see BEHAVIORAL ARCHAEOLOGY), symmetrical archaeology (see SYMMETRICAL ARCHAEOLOGY), and finally a growing interest in

the materiality of identity processes as a powerful tool for the understanding of social organization, social cohesion, ideological constructs, allegiances, and conflictuality when contextually observed.

In spite of general advances in archaeological thought (Trigger 2006) some criticalities can be pointed out. Archaeological practice can be synthetically described according to four consecutive steps, useful to highlight major shortcomings in the discipline:

1. *Archaeological project design*: All research and rescue archaeological projects need a precise plan regarding the cultural objectives, planning of the team composition required in the field, together with the proper archaeological staff, of bioarchaeologists, geomorphologists, conservators, surveyors, and possibly of other scientists that will be involved in the analytical processes of the postexcavation procedures.
2. *Survey and excavation*: a good technical standard in regional or site survey (see FIELD SURVEY), excavation procedures (see TERRESTRIAL EXCAVATION), materials and systematic samples collection (see ARCHAEOLOGICAL RECORD), and field recording techniques (see ARCHAEOLOGICAL FIELDWORK) has been attained, although in some cases, fortunately a minority, survey and stratigraphic excavation techniques and sample systematic are not properly followed. What is still lacking are strict protocols, both in surveying procedures and material collection, however, the contribution from biology, geochemistry, genetic, mineralogy, and other sciences is pushing archaeologists to establish such protocols to allow inter-site and regional comparisons to deal with the high variability and multiplicity of the social and economic organization of human groups. As an outstanding example of inclusive project organization we can mention the renewed excavation at the Neolithic site of Çatalhöyük.
3. *Postexcavation*: over the last 20 years this phase of archaeological research has seen a more comprehensive approach where archaeologists and scientists of different scientific branches have collaborated both

in the field and laboratories to gain a more effective understanding of human societies' cultural processes. However, this growing phenomenon needs a cultural revolution that necessitates more effective communication among archaeology and other scientific disciplines to overcome the distance between the humanities and hard science languages. It in practice requires the archaeologist to be trained, through university courses, to deal with the basic "language" of hard sciences and, on the other side, for scientists to be trained to properly understand the basic principles and directions of the archaeological discipline. Recent publications, however, are helping to highlight opportunities and cultural limits in the integration process of hard sciences in archaeology.

4. *Publication*: finally we have to bemoan the persisting dominance of traditional approaches to the final publication of archaeological excavations with scientific reports confined separately in adjoined sections of the reports. Nevertheless, the marriage between hard sciences and archaeology, celebrated over the last 20 years, will surely generate new archaeological questions and new avenues for more inclusive and broad-based narratives on the history of humankind.

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Archaeometry

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The emergence of the term archaeometry was a direct consequence of establishing the Research Laboratory of Archaeology and the History of Art at the University of Oxford in 1955. The Oxford Research Laboratory was founded through the combined efforts of a physics professor, Lord Cherwell, and an archaeology professor, Christopher Hawkes, for the application of the physical sciences to the solution of archaeological questions (Hawkes 1986). In the beginning, the Research Laboratory was principally concerned with the chemical analysis of pottery, and metal artifacts and coins; physical methods of dating such as magnetic dating (see *ARCHAEOMAGNETIC DATING OF BAKED CLAY FEATURES*) and, later, thermoluminescence dating (see *DATING CERAMICS AND LUMINESCENCE*); and prospecting for buried archaeological features such as kilns, pits, ditches, and roads using proton magnetometers (see *MAGNETOMETRY*).

The term archaeometry was then devised by Professor Hawkes in 1958 as the title of the Research Laboratory's Bulletin in which its early research was first published. The Bulletin very soon started to publish contributions by authors from other institutions, and thus became the international research journal, *Archaeometry*, of which there are now more than 50 published volumes.

The Oxford Research Laboratory also provided the impetus for the beginning of regular international archaeometry symposia. In 1962, a training course was organized for archaeologists who had purchased proton gradiometers (see *GRADIOMETRY*) from the Laboratory. During subsequent years, regular reunions of these gradiometer users were held in Oxford. Gradually the scope of these reunions expanded to cover other aspects of archaeometry until they eventually evolved into the annual (now biennial) International

Symposium on Archaeometry, of which there have now been more than 40.

In part because of the physical science base for the emergence of the term, archaeometry has tended to have been used in the context of artifact studies, physical methods of dating, and prospection for buried archaeological features, although both the journal and the symposia now routinely include biomolecular studies such as the analysis of organic residues in pottery (see *ORGANIC RESIDUE ANALYSIS*), stable isotope analysis of bone (see *DIET AND CARBON ISOTOPES* and *DIET AND NITROGEN ISOTOPES*), and DNA analyses (see *DNA: NEXT GENERATION SEQUENCING* and *DNA: MITOCHONDRIAL*). However, in new developments from the mid-1970s onwards, the term archaeometry has tended not to be used. Instead, terms such as science-based archaeology, scientific methods in archaeology, archaeological sciences, and archaeological science have been used to describe funding bodies, new undergraduate and postgraduate degree courses, and new lectureships and professorships.

As a result, with the exception of its use for the journal and symposium, archaeometry is now a more-or-less obsolete term, and has been subsumed and replaced by the term archaeological sciences (see *ARCHAEOLOGICAL SCIENCES*), which embraces the application to archaeology of the environmental and biological sciences, as well as the physical sciences.

SEE ALSO: Archaeomagnetic Dating of Baked Clay Features; Dating Ceramics and Luminescence; Magnetometry

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Archaeomineralogy

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The term archaeomineralogy is comparatively new. It was used by Rapp for a book, and by Rapp (2008) and by Kostov as part of the first international meeting on archaeomineralogy held in Sofia, Bulgaria. Archaeomineralogy is quite distinct from the history of mineralogy. It can be considered a subdiscipline of geoarchaeology (see GEOARCHAEOLOGY) as it covers the exploitation of rocks and minerals since ancient times for medicines, implements, ornaments, building materials, paints, and as raw material for metals, ceramics, and other processed products. Archaeomineralogy seeks to date, source, and characterize artifacts made from earth materials. Mineralogy as a field of investigation is closely connected to geosciences such as geology, petrology, and geochemistry, although it also has the strong tendency to embody the methods and techniques of modern crystallography and advanced materials science.

Archaeomineralogists, although not called by this term, go back to ancient times and were located around the globe. Among the most prominent were the Hellenistic Greek philosopher Theophrastus (ca. 372–287 BCE), the Greek physician Dioscorides (ca. 40–90 CE), the Italian Pliny the Elder (ca. 23–79 CE), the Spaniard Isidore of Seville (ca. 560–636 CE), the Arab authors Al-Biruni (973–1048) and Avicenna (980–1037), the Chinese Su Song (1070), the Italian Albertus Magnus (ca. 1206–80), and the German Georgius Agricola (1494–1555). Sanskrit texts from India mention the use of a wide variety of minerals in medicine (Rapp 2009). Modern practitioners of archaeomineralogy are mostly either geoarchaeologists who specialize in geology or lithology and have a background in mineralogy or petrology (origin and composition of rocks) or historians of science. Arguably, their mineralogical background makes them ideally

suited and well equipped to meet the demanding challenges posed by archaeometric analysis and conservation problems (Artioli 2010; Artioli and Angelini 2011).

Recently, provenance determination has become a significant aspect of archaeomineralogy. The provenance of exploited rocks and minerals can lead to the determination of trade routes, economic history, and other important aspects of society.

Ancient Egyptians had one of the best understandings of mineralogy and lithology in the practice of medicine and the manufacture of monuments and ornaments (Lucas and Harris 1999). Rock names such as basalt, syenite, porphyry, and alabaster have their origins in Egypt. The igneous rock “basalt” appears to have the oldest roots, in use as early as 2000 BCE. The Egyptian doctors knew the antacid properties of limestone and used kaolin to extract water or toxins from the stomach. They used approximately 20 minerals in medicinal preparations, including ruby, sapphire, emerald, jade, topaz, garnet, and feldspar, as well as pearl, coral, and shell. Ancient Mesopotamians also had a well-developed understanding of rocks and minerals for medicinal and industrial uses. Cuneiform texts record the use of minerals for medical treatments and a variety of drugs.

In ancient times, color was by far the most important character to classify rocks and minerals. Colors had significant symbolic attributes such as purity, passion, danger, and mourning. Many minerals and rocks had medicinal and magic properties. Alchemists equated color with the true nature of a substance. Modern understanding of the physical and chemical nature of mineral properties was established only in the early nineteenth century by Joseph-Louis Proust's law of constant composition in 1799, John Dalton's atomic theory in 1805, and the development of accurate methods of chemical analysis.

Early rock and mineral identification was chancy, most often relying on color alone. Names given to many mineral species have changed over time and even today some minerals have a variety of names and synonyms. For example, over 40

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names have been given to opal and its varieties. More than a thousand names have been given to rock lithologies. Nevertheless, sorting out what rocks were exploited in antiquity is somewhat easier than for minerals.

The feldspars are the most common minerals in the Earth's crust and are major constituents in most igneous rocks. In the Americas, ancient societies used semiprecious varieties (sunstone, moonstone, and amazonstone) as gems. Moonstone shows an opalescent play of colors. Amazonite was used as a gem by the pharaohs of Egypt and the kings of ancient Ur. In the New World, it was exploited by the Aztecs and the Maya.

The other mineral group that was widely available and extensively exploited was the quartz family (Götze and Möckel 2012). Rock crystal is colorless and transparent quartz. Vessels and spheres have been formed from large quartz crystals over vast time and space. Rock crystal and agate were favorite semiprecious stones throughout early China.

Quartz was used widely in gems, beads, seal stones, and ceremonial objects. The Greeks knew how to use shaped quartz crystal to concentrate the sun's rays to start fires. Many varieties of quartz have been used as semiprecious stones such as amethyst (purple or violet), citrine (yellow), and carnelian (red). Agate is varicolored microcrystalline quartz, often with irregular or concentric bands. The earliest use of agate was in Mesopotamia, where ornaments and tools have been recovered. Agate was the preferred stone for crafting signets, stamps, and seal stones throughout the ancient Near East. The area of Idar-Oberstein in Germany supplied agate to the Greeks and Romans.

Another silica mineral, opal, is a glassy not a crystalline material. The name opal may have been derived from the Sanskrit word *upala* meaning precious stone. For the Romans, opal ranked second only to emerald as a noble gem. Mexico's ancient societies had many sources of precious opal. Ordinary opal was used in the New World for projectile points. Another glassy material is obsidian, a normally black volcanic glass widely available in young volcanic terrain but entirely absent in other geologic settings. Although mainly used for tools and weapons, it was also made into ornaments. Neolithic sites in Anatolia are particularly rich in obsidian artifacts.

Obsidian also was important in many New World contexts. The Aztecs used obsidian for projectile points, knives, razors, swords, mirrors, and ornaments. Obsidian Cliff in Yellowstone National Park is one of the high-grade obsidian deposits in western North America.

Many silicate minerals have been used as gems (see GEMSTONES) because of their hardness and variety of colors. Sugilite, a relatively rare pink to purple silicate mineral, is one of a number of unusual gemstones found in Japan. Another is gem-quality hornblende.

Garnets are found on every continent except possibly Antarctica. The gem varieties are grossularite, almandine, pyrope, rosolite, hessonite, andradite, and uvarovite. Color is the most obvious feature of gem garnets. The garnet group shows one of the widest varieties of color in the mineral world, ranging from colorless, through white, gray, yellow, yellowish green, green, yellowish brown, brown, pink, red, and black. Only blue is missing. Principally used as a gemstone, the name grossularite originates from the Latin *grossularium* (gooseberry). During the Middle Ages, deep blood-red almandine garnet was preferred as a gemstone for decorating religious artifacts.

Lapis lazuli is known for its blue color, which can vary from deep blue, indigo blue, azure blue, and violet blue to greenish blue. Its name is derived from the Latin word for stone and a Persian word for blue. The only proven ancient source of lapis lazuli in the Old World is Badakhshan, Afghanistan (Moore and Woodside 2014). Lapis lazuli found its way to the Indo-Pakistani region by Neolithic times. The mines of Badakhshan were described by Marco Polo, who visited them in the thirteenth century. Importation of lapis began as early as the Third Dynasty at Ur for cylinder seals and beads. It found its way into Egypt by Predynastic times.

Jade is the gem term used for two different minerals, jadeite and nephrite. Jades have been worked into ornaments and implements since Neolithic times. Usually thought of as a gemstone, the toughness and ability to hold a sharp edge made jade a useful tool and weapon material. Ancient China is well known for its use of jade. As early as the Han Dynasty, Chinese craftsmen had the ability to distinguish true jade from look-alike imposters. Chinese jade (nephrite),

however, did not come from China. It came from nearby Burma and Turkistan.

Beryl may occur in gem forms as emerald (green), aquamarine (blue), or morganite (pink-red). Emeralds were Cleopatra's favorite gemstone. The earliest emeralds were mined from the legendary Cleopatra's Mines in the Sikait-Zabara region of Egypt. Until the Europeans discovered emeralds in the New World (Colombia and Brazil), Egypt was the only source. In India's most famous temple, dedicated to the goddess Minakshi, her idol is made of emerald, most likely carved out of a single crystal. Aquamarine is a beautiful sea-blue variety of beryl. The color is caused by iron ions in the crystals. The best of the gem-quality aquamarine is found in Brazil, where it occurs in pegmatites and associated alluvial deposits of gravel. Other localities include Russia's Ural Mountains, Afghanistan, Pakistan, and India.

Chrysoberyl has long been a favorite gemstone because of its beauty and hardness. It is found in two varieties, alexandrite and cat's eye. It has an extensive color range and can be found in various shades of yellowish green, yellow, gray, brown, blue green, and emerald green. Its name is taken from the Greek word *chrysos* (golden) and from the mineral beryl, in allusion to its color and beryllium content. The variety alexandrite is unique because the color depends on the light source. It is green or blue green in daylight and under fluorescent light, but shades of red when seen in incandescent light. Alexandrite was discovered in the 1830s in Russia's Ural Mountains and named after the future Czar of Russia, Alexander II.

Turquoise has a color that varies from bright blue, pale blue, sky-blue, bluish green, apple-green, to greenish gray. It is one of the oldest known talismanic and curative gems, prized by many societies worldwide. Turquoise was used in ancient Egypt prior to the First Dynasty, with mines operated in the Sinai Peninsula by the fourth millennium BCE. Turquoise was mentioned by the Arab mineralogist ibn-Mansur in 1300 CE. Turquoise has been exploited in China for more than 3,000 years, at least back to the late Shang at Anyang. There are a significant number of turquoise deposits in the southwestern United States, that continued to be worked and were exploited by ancient groups.

Corundum is found in two gem varieties: ruby and sapphire. Ruby is red in color and takes its name from the Latin *rubeus* (red). According to medieval Arab scholars, this stone was mined in Sri Lanka. Pliny listed sources as India, North Africa, Caria, Ethiopia, Miletus, Orchomenos, Chios, Corinth, Troezen (in Greece), Marseilles, and Lisbon. Sapphire is found in shades of blue and sometimes yellow. Sapphire is an ancient term of uncertain origin, possibly related to Hebraic *sappir* and Sanskrit *sanipruja*. Sapphire was used as a gemstone beginning in the early first millennium BCE.

Amber is not a mineral, but rather fossilized resin exuded by several plants, such as the conifer *Pinites succinifer* (Artioli and Angelini 2010). The name is taken from Arabic *acnbar*. Some varieties are called succinite (or Baltic amber) and retinite. Amber has a hardness of only 2.5–3.0. Artifact amber is quite susceptible to weathering and to poor conservation techniques. The color ranges from golden yellow through orange, red, brown, green, violet, and black. It can be transparent to opaque. Amber from various sources, when exposed to ultraviolet light, will fluoresce with different colors including red, green, blue, and yellow. Most modern amber from the Dominican Republic is golden brown or iridescent blue, depending on whether it is viewed under or against direct sunlight.

Diamond is the hardest natural mineral. It can be colorless, but it is also found in white to blue white, gray, various shades of yellow, brown, orange, pink, red, lavender blue, green, and black. Craftsmen in India used diamonds to drill holes in hard gems like beryl to make beads. Europeans were not aware of India's diamonds until Marco Polo visited the area in the thirteenth century CE. Because diamond forms in a rare igneous rock called kimberlite, its occurrences are limited.

Pearl is composed of the calcium carbonate mineral aragonite produced within the soft tissue of a living shelled mollusk. The highest quality pearls come from the genus *Pinctada*. Pearls are characterized by their translucence and luster with an intricate play of surface colors. The iridescence results from the refraction of light through many layers. The color of pearls varies with the type of mollusk species as well as the water environment it grew in. Pearls can be found in white, yellowish white, pinkish white, bluish

white, reddish, and blackish gray. The earliest use of pearl as a gem appears to be in Europe and dates to the Paleolithic. Freshwater pearls have also been found in rivers in the British Isles and continental Europe. In modern times, saltwater pearls (mostly cultured) are harvested from the northwestern Pacific Ocean, particularly the waters around Japan. The technique for growing cultured pearls was developed by the Japanese in the early twentieth century.

The Bible has over 1,700 references to gems and minerals under 124 Greek and Hebrew names. Many cannot be identified from the biblical text, and others are obscure. One of the most detailed descriptions in the Old Testament is of a breastplate worn by the high priests of the temple; it contained 12 gemstones representing the 12 tribes of Israel. These gemstones were ruby, chrysotile, beryl, turquoise, sapphire, emerald, jacinth, agate, amethyst, topaz, onyx, and jasper. In medieval times these same 12 gems became affiliated with the 12 signs of the zodiac. The modern custom of birthstones is derived from this tradition.

Rocks and minerals that have been altered by humans are found throughout the archaeological record from very early periods (Nassau 1994). For example, the ancient Romans valued darker chalcedony over lighter varieties, and they learned that burning light-colored chalcedony would cause it to darken. Examples of altered color can also be found in obsidian, tourmaline, and sapphire. In dealing with the color of minerals in antiquity, we do not know when early producers discovered that the color of many minerals could be changed by heating; in most cases, methods for heat-treating gemstones became a closely guarded trade secret. Modern technology has provided methods to duplicate natural gems and semiprecious stones (see GEMSTONES); all manner of gem crystals from beads to large pendants can nowadays be produced on a massive scale.

Being able to identify fake gems and semiprecious stones is *theoretically* easy since each has a unique set of physical and chemical properties. The synthetics are designed to have the look and color of a natural gemstone, but most do not have either the chemical or physical characteristics of the natural material. It remains possible to identify the fakes with the proper scientific equipment, particularly optical, but it is difficult

if the only equipment is the unaided eye with a 10-power hand lens, a hardness set of some sort, and a way to measure the density. Highly polished and highly reflecting materials such as gemstones are especially difficult to identify without analytical tools. Artificial gemstones may have a more vivid color than their natural counterparts. Synthetic corundum, including those simulating ruby and sapphire, can be manufactured to have chemical and physical characteristics that are nearly identical to the naturally occurring gemstones.

Rocks are mineral assemblages. They are distinct from individual mineral species and they have played a significant role in the development of society. Lithic resources have been used since our ancestors first threw rocks as weapons and made crude stone tools. Useful rocks are unevenly distributed throughout the world, so trade and exchange developed early. Many distinct properties of rocks can lead to their utilization, that is, hardness, massiveness, convertibility through processing to useful materials (e.g., clays fired to ceramics), and so on.

The Romans discovered that a finely ground mixture of pumice and lime would make a cement that was far superior to lime mortar. It would even set under water (Brandon et al. 2014). Basalt is one of the oldest rock names in use, as well as one of the earliest rocks exploited. It was used for building blocks, monuments, and statues, as well as grindstones, mortars, mauls, and pestles. The term granite refers to a specific type of igneous rock, but also has been used more broadly for igneous building stone. In South America the famous high mountain fortress of Machu Pichu was built largely of granite.

Well-indurated sandstone has been used as a building material since humans first learned how to quarry it. The great pyramid of Cheops at Giza was constructed of limestone, and limestone tools have been made since the Paleolithic. The first use of the term limestone was in the literal sense: a stone from which lime could be extracted (Barba Pingarrón and Villaseñor Alonso 2013). Marble, metamorphosed limestone, has been a major building stone since antiquity, in part because it is softer and much easier to shape than igneous rocks.

Throughout much of the Near and Middle East, where hard rocks are unavailable, clay-based

material has been used for mud brick and related building materials. Most earthen materials are processed mixtures formulated to contain binders, filler, material to control shrinkage, and so on. An important earthen building material is the various forms of rammed earth, including pise and humra.

SEE ALSO: Adobe; Archaeological Sciences; Archaeometry; Cements, Mortars, Binders; Characterization of Ceramics; Characterization of Metals and Alloys; Characterization of Pigments; Chemistry in Archaeology; Glass and Faience; Glazes, Slips, and Paints; Obsidian Hydration Dating; Ore and Smelting Slag

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Dating in Archaeology

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Introduction

Archaeologists study the lives and activities of humans through the analysis of remains that catalogue that history, and these include fossils, artifacts from occupation sites, and other physical relics. A critical element in such studies is the assignment of a temporal framework to the observed features. More often than not, archaeological materials are found among earth materials. Hence, it is not surprising that dating methods used in archaeology borrow largely from geochronological methods that are used in the earth sciences. The choice of the method that is ultimately employed for any dating exercise is determined by the dating range that is under consideration as well as the types of materials that are available for analysis.

For context, Figure 1 outlines some major milestones of human evolution as well as dating methods that are commonly used in archaeology. It is generally thought that the human lineage diverged from that of chimpanzees around 5–7 million years (Ma) ago or earlier (e.g., Langergraber et al. 2012). Following a number of evolutionary steps (Figure 1), *Homo sapiens* emerged and subsequently spread from Africa into Europe and Asia, starting from around 200 thousand years (ka) ago. By ca. 70 ka, *Homo sapiens* had spread to southeast Asia, reaching Australia around 50–65 ka ago. Humans are only thought to have spread through the Americas after 20 ka. This evolutionary timeline demonstrates that the utility of the dating ranges outlined in Figure 1 varies geographically. When working in Africa, for instance, dating methods that collectively cover all stages of human evolution from around 7 Ma would be expedient. In the Americas, however, methods that only cover the last 30 ka would suffice.

On the basis of their operational principles, dating methods outlined in Figure 1 can be classified into four main categories (e.g., Lowe and Walker 2015). The first group comprises methods that are based on radioactive decay of unstable isotopes. These include radiocarbon, argon isotope, uranium series, luminescence, electron spin resonance and fission-track dating methods. The second category comprises dating methods that are based on pattern recognition, such as annually banded records that can occur in tree rings and lake sediments. The third group consists of methods that use age-equivalent markers for correlating time units. Such markers include stratigraphic indicators that are employed in paleomagnetism as well as layers of tephra from volcanic eruptions. More recently, biological markers have also been used. The final group comprises methods that can only be used for comparative or relative dating. In addition to basic stratigraphic ordering, relative dating methods include chemical dating methods such as obsidian hydration, amino acid geochronology, and fossil bone analysis (Lowe and Walker 2015). Dating can also be performed using chronological typology, which assigns ages to features using physical characteristics associated with societies whose ages are known. The principles behind the methods presented in Figure 1 are briefly outlined below.

Dating methods based on radioactivity

Radiometric dating methods include techniques that compare the abundance of an unstable parent nuclide in a given material to that of the daughter nuclide produced by radioactive decay. Together with the rate of decay, the information is used to determine the amount of time that has passed since the beginning of a particular event. Such methods include radiocarbon (see RADIOCARBON CALIBRATION AND AGE ESTIMATION), argon-isotope (see ARGON-ARGON DATING) and uranium-series (see URANIUM-SERIES) dating methods. Other methods based on radioactivity include techniques that evaluate cumulative

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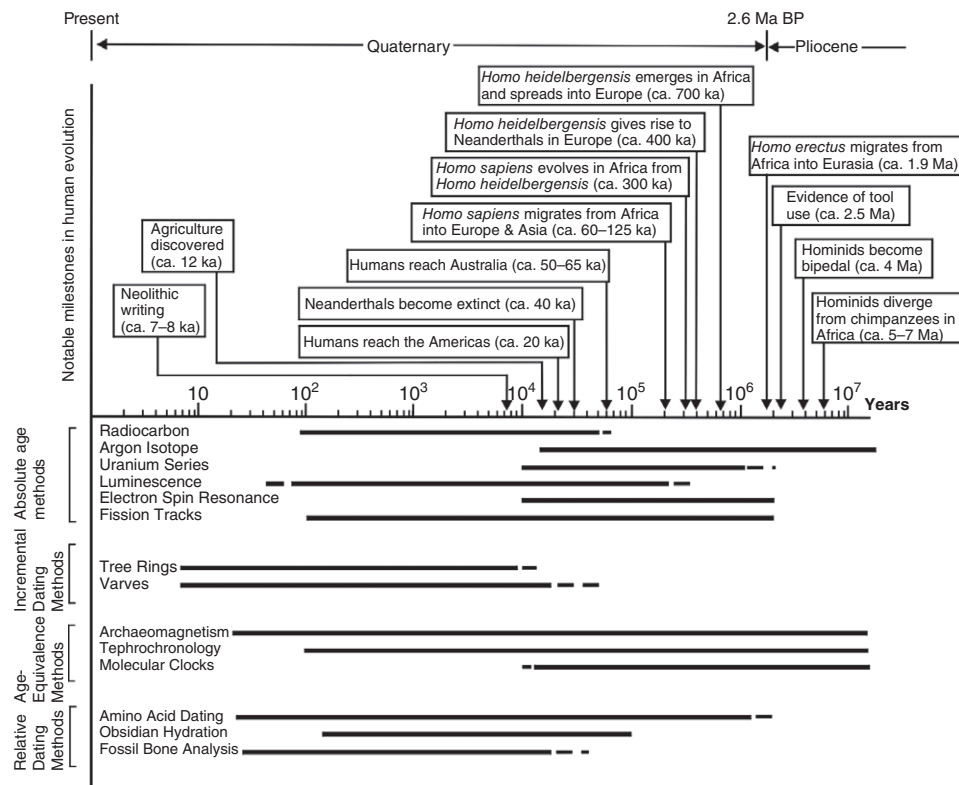


Figure 1 Diagram of the notable milestones of human evolution, as well as the most commonly used dating methods and their applicability in archaeology. Modified after Walker, 2005, p. 14.

radiation damage since the start of a given event. Radiation damage methods include luminescence (see THERMOLUMINESCENCE), electron spin resonance (see DATING AND ELECTRON SPIN RESONANCE (ESR)) and fission-track dating techniques.

Radiocarbon dating

Natural carbon comprises three isotopes: ¹²C, ¹³C and ¹⁴C. Radiocarbon (¹⁴C), which occurs in trace amounts, is unstable and undergoes radioactive decay. In nature, radiocarbon is mostly produced in the upper atmosphere when nitrogen atoms interact with neutrons generated by cosmic rays. The ¹⁴C reacts immediately with oxygen to form carbon dioxide (CO₂) that diffuses throughout the atmosphere. When plant material assimilates CO₂ as part of photosynthesis, it takes up some ¹⁴CO₂. Animals that eat the

plant material also take up ¹⁴C. As a result, the ¹⁴C concentration in all living organisms is similar to that of the atmosphere. When an organism dies, however, it stops taking up ¹⁴C. Hence the concentration of ¹⁴C that it contains begins to decline as the radiocarbon decays. If at any time, a determination is made of what proportion of the original ¹⁴C atoms are still remaining in the organic material, the amount of time that has passed since the organism died can be determined. Radiocarbon years (see RADIOCARBON CALIBRATION AND AGE ESTIMATION) need to be calibrated before they can be compared with calendar years. Archaeological materials that can be dated using radiocarbon include well-preserved organic material such as wood, seeds, charcoal, and bone and other faunal remains. Radiocarbon can generally be used for dating material up to ca. 50 ka old (Ramsey 2008).

Argon isotope dating (K–Ar, Ar–Ar)

Potassium (K) has an unstable isotope (^{40}K) that undergoes a branched decay to yield isotopes of calcium (^{40}Ca) and argon (^{40}Ar). Only the ^{40}Ar branch of the decay is useful for radiometric dating. In archaeology, the dating is usually applied to volcanic rocks that are interbedded with sedimentary units that contain artifacts or fossils. Argon, a gas, escapes when volcanic rocks are molten. When the rocks cool, however, the radiogenic argon is trapped within potassium-bearing minerals. Over time, ^{40}Ar accumulates in the mineral. By measuring the amount of ^{40}Ar , it is possible to estimate the time that has passed since the rock formed (Chernyshev, Lebedev, and Arakelyants 2006). In ^{40}K – ^{40}Ar dating, measurements of ^{40}K and ^{40}Ar are made on separate sample aliquots, which can introduce error when dealing with heterogeneous materials. However, dating using ^{40}Ar – ^{39}Ar (see ARGON–ARGON DATING), which only measures a single aliquot, circumvents the problem. With this approach, the concentration of ^{40}K is ascertained by irradiating the sample in a nuclear reactor to convert ^{39}K to ^{39}Ar . Since the abundance of ^{39}Ar will be proportional to that of ^{39}K , and the abundance of ^{39}K proportional to ^{40}K , a mass spectrometer can be used to determine the ratio of ^{40}K to ^{40}Ar in a single measurement. The much greater sensitivity of ^{40}Ar – ^{39}Ar dating compared with ^{40}K – ^{40}Ar dating allows smaller samples to be analyzed using the former technique. The dating range for argon isotope dating spans from ca. 13 ka to over 4,000 Ma, which makes it a very versatile technique in archaeology.

Uranium-series disequilibrium dating

Isotopes of uranium (^{238}U and ^{235}U) and thorium (^{232}Th) decay through complex decay pathways to give ultimately stable isotopes of lead (Pb). Intermediate nuclides of the decay have a range of differing half-lives, but the overall half-life of each of the chains is too long to be used in archaeological dating. Nonetheless, a useful character of the uranium series decay is that the nuclides tend to behave differently during weathering and deposition, resulting in some of the intermediate nuclides being removed from the decay chains. When such interruptions occur,

the system enters a disequilibrium phase during which radiogenic nuclides start to accumulate anew, providing a mechanism for dating Quaternary events. Materials that can be dated using uranium-series (see URANIUM-SERIES) disequilibrium processes include carbonates extracted from solution, which will be enriched in uranium, for instance mollusks, speleotherms, corals, tufa, and travertines. Phosphates and fossil bone enriched with uranium could also be dated using the same technique. Sediment on ocean or lake floors will be rich in ^{230}Th and ^{231}P and could also be dated using a similar approach. The dating range for the uranium series disequilibrium systems is from ca. 10 ka to ca 1–2 Ma (Lowe and Walker 2015).

Luminescence dating

Luminescence dating is a collective term for dating methods that are based on the ability of some minerals, when subjected to ionizing environmental radiation, to absorb and store energy by trapping electrons in lattice defects. The ionizing radiation emanates from unstable isotopes of the uranium (^{238}U , ^{235}U) and thorium (^{232}Th) decay series as well as from ^{40}K that are in the immediate surroundings of the mineral grains. An additional small component of the radiation comes from cosmic rays. If the minerals are stimulated in a laboratory setting, the stored energy can be released as light and measured. Sample stimulation by heating yields thermoluminescence (TL), whereas exposure to an appropriate optical source gives optically stimulated luminescence (OSL) (see DATING AND OPTICALLY STIMULATED LUMINESCENCE). Dividing the stored energy (paleodose) by the rate at which the ionizing radiation was received (dose rate) allows a luminescence age to be determined (Equation (1)).

$$\text{Luminescence age} = \frac{\text{Paleodose}}{\text{Annual dose rate}} \quad (1)$$

Luminescence dating is generally performed using quartz or feldspar. Both minerals, when exposed to sunlight, are emptied (zeroed) of any previously accumulated energy. Alternatively, the grains could be heated to high temperatures to expel any trapped electrons. Hence, archaeological materials that can be dated using TL

include previously heated artifacts such as fired bricks, fired pottery or terracotta material. Burnt flint or other heated rocks can also be dated. For sediment dating, wind-deposited sand and silt or fluvial deposits that are adequately zeroed can be dated using OSL (e.g., Liritzis et al. 2013). The dating range for luminescence methods is from a few decades to ca. 150–200 ka, although older ages have been reported.

Electron spin resonance dating

In electron spin resonance (ESR) (see DATING AND ELECTRON SPIN RESONANCE (ESR)) dating, as in luminescence dating, ionizing radiation from unstable isotopes of the ^{238}U , ^{235}U and ^{232}Th decay chains, as well as from ^{40}K and cosmic ray radiation, can result in trapped charge in some materials. In this instance, the charge is in the form of paramagnetic electrons that are trapped in crystal defects of mineral grains or other substances. If such materials are exposed to high-frequency electromagnetic radiation within a powerful magnetic field, the trapped electrons become excited. When the magnetic field is changed, the resonance with the excited electrons can be detected. The resonance will be proportional to the number of trapped electrons and is equivalent to the paleodose. The dose rate can be calculated by evaluating the annual dose from the U and Th sources as well as from K and cosmic rays. Thus, the age can be determined using Equation (2):

$$\text{Electron spin resonance age} = \frac{\text{Paleodose}}{\text{Annual dose rate}}$$

Materials that can be dated using ESR include speleothems, corals, tooth enamel, mollusk shells, quartz in rocks and sediments, and burnt flint. Ages from ca. 10 ka up to 2 Ma can be obtained using ESR dating.

Fission-track dating

Radiation damage that occurs in mineral grains containing trace amounts of uranium can result in physical tracks that can be visualized and counted. Such damage occurs when the uranium undergoes spontaneous fission to form elements

of lower atomic number. Fission fragments collide with adjacent atoms of the mineral bearing the uranium, ionizing them to form the damage trails. The tracks can survive in the material for millions of years. Hence, they accumulate over time. By determining the amount of uranium in the mineral grains as well as counting the tracks, the amount of time that has passed since the grain was formed can be determined. Fission tracks are used for dating volcanic rocks such as basalt, tephra, tuff, and pumice. The mineral zircon is usually targeted because it has a high uranium content and is common in igneous rocks. Obsidian has also been used in some studies. Alpha recoil-track dating works on the same principles as fission-track dating, with the exception that the recoil tracks that are counted are produced by alpha particles. Track counting ages can range from ca. 0.1 ka to ca. 2 Ma (Lowe and Walker 2015).

Incremental dating methods

Organisms as well as geological deposits that add an additional feature at regular intervals can be used to measure time. In archaeological dating, tree rings (dendrochronology) and sediment layers in lake deposits have been employed to provide invaluable timescales in some settings.

Dendrochronology

During spring and summer, some tree species add a new layer of tissue for conducting nutrients, following a winter of relative dormancy. The differences in the structure of the layers allow seasonal variations to be recorded as annual sets that can be counted to give age. Oaks and pines are some of the most commonly used species in dendrochronology. Notably, dendrochronology provides floating ages that would need to be pegged to the calendar scale using another chronometer such as radiocarbon dating. For archaeological dating, tree-trunk dating is usually performed on dead or fossil trees that are obtained from sedimentary basins, peat bogs, or archaeological sites. Cross-matching overlapping rings can also be used to extend the chronological

range covered by the tree rings. Dendrochronology produces very accurate ages. Consequently, it has been used to calibrate the radiocarbon scale back to ca. 14 ka (e.g. Reimer et al. 2013).

Varves

Sediment layers in lakes that show annually repetitive depositional cycles are referred to as varves (see *VARVE CHRONOLOGY*). The cyclical nature is usually a product of seasonal variations in the deposits brought into the lake. Dating using varves entails identification of the seasonal layers after which they are enumerated. By correlating ends of different varve sequences, it is possible to link them to create a longer timeline. However, like in dendrochronology, varve sequences form floating chronologies that need to be pinned to the calendar scale using another absolute chronometer. Once calibrated, varves provide very reliable timescales to the extent that they have been used to calibrate the radiocarbon timescale beyond the range of dendrochronology, which currently ends around 14 ka (e.g. Reimer et al. 2013).

Age-equivalent dating methods

Marker horizons that form synchronously across different stratigraphic sequences can be used as benchmarks for estimating ages of other geological units where the markers may be found. Genetic markers of evolutionary change in biological materials can also be used for the same purpose. Temporal markers that can be used for archaeological dating are found in paleomagnetism, tephrochronology, and biological molecular clocks.

Paleomagnetism/archaeomagnetism

The Earth's magnetic field changes over time in both strength and direction. Polarity changes result in the reversal of the magnetic field. When rocks that contain magnetic minerals form, they record these changes in the Earth's magnetic field. Similarly, when archaeological materials including pottery and hearths are heated to high temperatures, they record the Earth's ambient

magnetic properties when they cool. By measuring magnetic properties of well-dated artifacts, an archaeomagnetic record (see *ARCHAEO-MAGNETISM*) can be reconstructed for dating purposes. Archaeological materials from the last 10 ka can be dated using this approach. Magnetostratigraphy (see *MAGNETOSTRATIGRAPHY*) examines the variation of the magnetic characteristics of a sequence of earth materials. Such variations are used for relative dating of rocks, as well as for correlating geological units that formed contemporaneously. Additionally, because polarity reversals are global, when they are dated in volcanic rocks using another dating method such as the argon isotope method, a paleomagnetic timescale can be produced.

Tephrochronology

Explosive volcanic eruptions release material referred to as ash or tephra (see *TEPHRA AND VOLCANIC ASH ANALYSIS*) that can be carried by wind over large distances. When the ash settles on the ground, it creates an extensive isochronous unit that can exceed thousands of square kilometers in area and can serve as a useful stratigraphic marker (Lowe 2011). Tephra units can be dated using absolute dating methods such as radiocarbon or argon isotope methods. Once dated, other geological units interbedded with the tephra that may contain artifacts or fossils can be constrained.

Molecular clocks

Molecular clocks employ rates of mutation in biological molecules (e.g., DNA or amino acids) to estimate time that has passed since the divergence of given biological organisms (O'Reilly, dos Reis, and Donoghue 2015). Importantly, however, the molecular clock is not equivalent to a calendar scale and hence it cannot be used directly as an estimate of time without calibration. Thus, ages obtained using other dating methods are used as benchmarks that allow the rates to be ascertained. The chronological range over which the technique has been used spans from ca. 10 ka to over 600 Ma.

Relative dating methods

The stratigraphic law of superposition is an important principle in archaeological dating. The law states that, for geological units that lie undisturbed, oldest units lie at the bottom and youngest at the top. This allows archaeological materials to be assigned relative ages on the basis of their position in a stratigraphic sequence. In the absence of a distinct stratigraphy, seriation can be used whereby relative ages are assigned on the basis of the frequency of occurrence of cultural artifacts whose ages are known. Natural alteration processes that depend on time can also be used to rank archaeological materials in order of the extent of the change as a means of relative dating. Figure 1 presents three types of such relative dating: amino acid dating, obsidian hydration dating, and the analysis of fossil bone.

Amino acid dating

Most amino acids, the building blocks of proteins, can occur in two forms referred to as isomers. The isomers have similar chemical properties, but when exposed to plane-polarized light, they rotate it in opposite directions, with L-amino acids rotating the light to the left while D-amino acids rotate it to the right. Living organisms only contain L-amino acids. When the organisms die, however, L-isomers are converted to D-isomers until an equilibrium is reached. Thus, by measuring the degree of L to D conversion in a material, a relative age can be estimated. Suitable materials for amino acid analysis include mollusk shells, eggshells and other protein-bearing organic remains (Lowe and Walker 2015).

Obsidian hydration dating

Obsidian is volcanic glass. When exposed to the elements, obsidian absorbs moisture, which results in a hydrated layer referred to as perlite. The thickness of the perlite is partly dependent on the duration of exposure to the elements. Other factors that affect the thickness include the geochemistry of the obsidian, temperature, and humidity. Hence, the utility of the method is mostly restricted to comparing relative ages of

samples from the same site (Lowe and Walker 2015). Archaeological applications of obsidian dating (see OBSIDIAN HYDRATION DATING) have largely been in dating artifacts made from obsidian.

Fossil bone analysis

Fluorine and uranium are elements that preferentially accumulate in fossil bone (see BONES AND IVORY) buried below ground. Although the rate at which the chemicals are taken up by bone is influenced by local factors, it is also time-dependent. This allows fossil bones to be assigned relative ages on the basis of their uranium or fluorine content. In contrast with uranium and fluorine, which increase in buried bone over time, nitrogen in fossil bone decreases as the bone degrades. Hence, by measuring the remaining nitrogen content, it may be possible to assign relative ages to fossil bones, with lower nitrogen content denoting older ages. Fossil bone analysis can be used to compare ages of bones up to 40 ka old (Lowe and Walker 2015).

SEE ALSO: Climate Change and Dating; Cosmogenic Dating; Dating Ceramics and Luminescence

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Diffraction

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Diffraction effects are produced by a crystal lattice through the interference of waves (or particles described as waves following the De Broglie concept of wave–particle duality) having wavelengths compatible with interatomic distances. The effect was first observed by Laue and coworkers over 100 years ago. This seminal experiment demonstrated at the same time that crystals are composed of periodic arrangements of atoms, and that X-rays are electromagnetic waves. Since then crystallographic diffraction techniques based on the interference of X-rays, neutrons (see NEUTRON DIFFRACTION (ND)), or electrons (see TRANSMISSION ELECTRON MICROSCOPY and ELECTRON BACKSCATTER DIFFRACTION (EBSD)) have developed rapidly and become routine tools in the analysis of materials of different nature, including all the natural and human-made materials involved in human activities and forming the archaeological record (see ARCHAEOLOGICAL RECORD) (Artioli 2013). Although commonly used to analyze crystalline compounds, XRD can also be applied to disordered and amorphous compounds producing only diffuse scattering (Guinier 1994). Furthermore, even materials that are normally considered amorphous, such as glass, glaze or glassy materials (see GLAZES, SLIPS, AND PAINTS), may contain a significant number of crystal phases that can yield information on their origin and manufacturing techniques (Artioli, Angelini, and Polla 2008).

Among the variety of techniques presently available for the characterization of materials, diffraction is unique insofar as it is intrinsically sensitive to the ordered (i.e., periodic, symmetric) atomic structure of crystals. Information provided by diffraction techniques include: (1) phase identification and quantification of crystalline compounds and complex polyphasic mixtures; (2) the texture and orientation of crystalline

phases in a material (see METALLOGRAPHY AND CRYSTALLOGRAPHIC TEXTURE ANALYSIS); (3) the atomic and molecular structure of the phases involved; and (4) the physical microstructural state of the material.

Experimentally, the diffraction effects produced by the interference of electromagnetic waves or particle beams with crystalline matter can be directly related to the properties of the crystal phases present in the system (Giacovazzo et al. 2011). The measured sample can be a single crystal (i.e., *single crystal diffraction*), or a large ensemble of crystals (i.e., diffraction from *polycrystalline samples*, or *powder diffraction*) either having the same crystal-chemical nature (monophasic sample) or, more frequently, being a mixture of different crystal phases (polyphasic samples). In all cases, the measured diffraction effects in reciprocal space (or *diffraction patterns*) are interpreted by the simple geometrical relationship described by *Bragg's law*:

$$2d_{hkl} \sin \theta = n\lambda$$

where d_{hkl} is the spacing between the atomic planes in the crystal, λ is the wavelength of the incident radiation, and 2θ is the diffraction angle, that is the angle between the incident beam and the diffracted beam. For any given λ , positive interference (i.e., diffraction) occurs only at the angles satisfying Bragg's conditions for all possible atomic planes in the crystal. Each family of atomic planes d_{hkl} has a specific orientation (defined by the so-called *Miller indices*, hkl) with respect to the crystallographic base vectors, which define the crystallographic unit cell within the periodic crystal lattice.

The investigation of the arrangement of atoms within each crystal phase (i.e., the *crystal structure*) is one of the main tasks of *crystallography* (www.iucr.org). Every solid compound at any given pressure and temperature has a unique crystal structure that minimizes Gibbs free energy, and that it is ultimately controlled by the formation of interatomic chemical bonds. The crystal structure of a solid phase therefore is described by (1) the crystallographic *unit cell*;

(2) the *space group symmetry*; and (3) the type and position of each atom in the unit cell.

Diffraction techniques in essence yield very basic information on the nature of the material, its physical state, and its crystal-chemical arrangement at the atomic and molecular level, providing a means of identifying, characterizing and interpreting crystalline compounds from simple elemental and ionic solids to complex macromolecules. The atomic structures of known crystalline compounds are listed in available databases (ICSD: Inorganic Crystal Structure Database, www.fiz-karlsruhe.de/icsd.html; CSD: Cambridge Structural Database, www.ccdc.cam.ac.uk/products/csd/; MSA-CSD: Mineralogical Society of America Crystal Structure Database, www.minsocam.org/MSA/Crystal_Database.html), and they are essential references for identification and analytical purposes.

Because of the fact that most geological and archaeological materials are polycrystalline and polyphasic, with the notable exception of gemstones (see GEMSTONES), and because of the wide availability of X-ray sources in scientific laboratories, the preferred diffraction technique universally adopted for analytical purposes of geomaterials and archaeomaterials is X-ray powder diffraction (Dinnebier and Billinge 2008). The measured powder pattern (generally described in terms of relative intensity vs Bragg angle or d-space) corresponds to a one-dimensional projection of the reciprocal space, and each measured Bragg peak corresponds to a specific atomic plane within a crystal phase. The analysis of the position and intensity of the peaks allows for straightforward identification and quantification of the crystal phases present in the system. The most complete and advanced method for the modeling and extraction of information from powder diffraction patterns is called *full profile analysis* (or *Rietveld analysis*) (Young 1993).

Modern diffraction techniques applied to heritage materials focus on: (1) *noninvasive measurements*, that is, the analysis of the object without sampling; (2) *2D and 3D crystal phase mapping*, that is, imaging the distribution of crystal phases on the surface or within the body of the investigated objects (also referred to as *diffraction imaging* or *diffraction-enhanced tomography*); and (3) performing *simultaneous and combined*

measurements, in order to provide combined information from diffraction, imaging (see IMAGING) and spectroscopy (see SPECTROSCOPY) on the same sample.

On the one hand, X-ray based diffraction techniques, especially using micro-beams produced by synchrotrons (see SYNCHROTRON-BASED X-RAY ANALYTICAL TECHNIQUES AND MATERIALS ANALYSIS), have the advantage of yielding data with high spatial resolution and low penetration. They are ideal for micro-samples, 2D crystal phase mapping, and surface analysis. On the other hand, neutron beams (see NEUTRON DIFFRACTION (ND)) can be used at low spatial resolution to penetrate thick and dense objects. They are ideal for bulk samples and 3D crystal phase mapping. *Crystallographic texture analysis* (see METALLOGRAPHY AND CRYSTALLOGRAPHIC TEXTURE ANALYSIS) using neutron or high-energy X-ray diffraction has been proposed as a totally noninvasive metallographic method to interpret the manufacturing of ancient metals. Diffraction techniques therefore provide a wide range of powerful tools for investigating all kinds of materials involved in archaeological issues and problems.

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Electron Backscatter Diffraction (EBSD)

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In the field of heritage studies, a variety of materials may be encountered in different studies concerning art objects, monuments and artifacts in general. Glass, stone, ceramic, mortar, and metal are only a few examples of materials (or part of them) that can have a crystalline nature, matching the basic condition for being analyzed by electron backscatter diffraction (EBSD) (Wanhill 2005; Peruzzo, Fenzi, and Vigato 2011; Gambirasi et al. 2013).

Diffraction of primary electrons of the scanning electron microscope (SEM) beam (see SCANNING ELECTRON MICROSCOPY) can occur when a crystalline material is placed under the beam (Figure 1). Such electrons, diffracted from the lattice planes of a submicron volume of the sample surface, can be collected if a suitable detector (phosphor screen) is placed very close to the sample. Diffracted electrons are intercepted by the screen drawing a pattern of dark and light intersecting lines ("Kikuchi lines"), which represent the crystal lattice geometry. This pattern is characteristic of the crystal structure and orientation of the point it was generated from, thus allowing a precise identification of the mineral phase and its absolute orientation in the space.

The discovery of the physical process on which EBSD is based dates back to 1928, when Nishikawa and Kikuchi recorded diffraction patterns from a calcite crystal on photographic plates and described them as "black and white lines in pairs due to multiple scattering and selective reflection." Over the next decades, several scientists studied this phenomenon, until, in the 1970s, the availability of commercial SEMs allowed great progress in projecting and implementing analytical systems using a phosphor screen and TV camera to record the patterns.

In present-day EBSDs, a high-resolution, high-speed charge-coupled device (CCD) camera is attached to the phosphor screen and connected to a computer-aided system able to rapidly detect and identify Kikuchi lines in EBSD patterns. The acquired pattern is automatically compared to a database of possible phases until a solution is proposed when the best-fitting phase from the database matches that pattern.

Diffraction patterns may be acquired by choosing each single grain, moving the SEM beam from grain to grain; alternatively, data can be acquired on a grid of points over a selected area of the surface of the sample. In both cases, the SEM beam can scan, at high magnification, over a small area of the sample without problems due to the variation of the angle of incidence of the beam with the surface. Conversely, operating at lower magnifications on a large area, the best procedure is to use a stationary beam and acquire the data by moving the sample by means of an automated specimen stage.

The nominal angular resolution limit is approximately 0.5 degrees, and the spatial resolution is related to the resolution of the SEM, which for modern field emission SEMs can be considered to be a few tens of nanometers. Exploiting the ability to scan the beam (or move the stage) over multiple points on the surface, it is possible to easily create an orientation map of a polycrystalline sample, where contiguous points producing similar diffraction patterns are recognized as being part of the same grain. In an orientation map, each differently colored area represents a grain with a distinct crystallographic orientation, allowing boundary characterization, grain size measurements, statistical studies on spatial relations, and preferred orientations quantification (Schwartz et al. 2009).

SEMs are usually equipped with energy dispersive X-ray spectrometry (EDS) systems for chemical analysis (see SEM-EDS AND MATERIAL ANALYSIS). Suitable software enables phases, also with very similar crystal structures but different chemistry, to be differentiated by simultaneously collecting an EBSD pattern and an X-ray

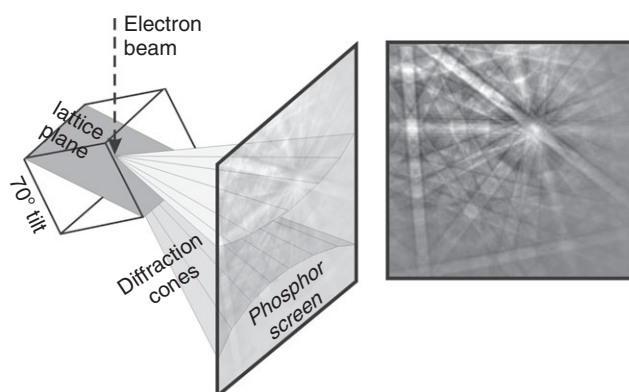


Figure 1 Principle of EBSD pattern formation.

Source: Republished with permission from Wiley in Peruzzo Luca, Fenzi Federica, and Vigato Pietro A. 2011. "Electron Backscatter Diffraction (EBSD): A New Technique for the Identification of Pigments and Raw Materials in Historic Glasses and Ceramics." *Archaeometry* 53: 178–193.

spectrum from each single point on the sample. Thus, EDS data are used to refine the EBSD solution at each point for more accurate phase identification (Nowell and Wright 2004).

Depending on the speed and resolution of the detector, automated pattern acquisition and evaluation is possible at a speed of up to several hundred patterns per second. Patterns can be saved during acquisition, and complete phase identification as well as map reanalysis is carried out offline at an ultra-fast speed of up to several thousand points per second.

These and other technological strengths of the EBSD technique provide powerful analytical tools when applied to archaeological disciplines. Some examples of investigation fields are: characterization of raw constituents and reaction phases originating during the production of materials such as colored, transparent, or opaque glass, mortars (see CEMENTS, MORTARS, BINDERS), and pigments in ceramics and paintings (see CHARACTERIZATION OF PIGMENTS and CHARACTERIZATION OF CERAMICS); study of transformation phases due to deterioration (see DETERIORATION); and analysis of crystallographic texture in metals and alloys (iron, bronze, silver) to infer the manufacturing process (see CHARACTERIZATION OF METALS AND ALLOYS and METALLOGRAPHY AND CRYSTALLOGRAPHIC TEXTURE ANALYSIS).

EBSD mapping, in the case of metal objects, permits a good quantitative representation

of the sample microstructure: a measure of the crystal orientation and angular mismatch between grains, examination of grain morphology, boundaries, and twins, and discrimination between different materials.

Even though EBSD has been widely employed for many years in modern metallurgy to obtain microstructural information from metals and alloys, the application of this technique to ancient metal artifacts is scarce (Zaghis et al. 2005; Mapelli, Nicodemi, and Riva 2007; Barnett, Sullivan, and Balasubramanian 2009). Only a few EBSD-based studies focus on ancient metallurgical processes, so the lack of reference literature and comparison examples is still one of the difficulties of applying EBSD in this research field, and this needs to be further explored.

As previously mentioned, another challenging aspect of EBSD is the possibility to identify unknown mineral phases discriminating among different but similar compounds. Phase identification obtainable through EBSD is often impossible to achieve by other methods such as X-ray diffraction, wavelength dispersive spectroscopy, and transmission electron microscopy, and, keeping in mind that samples coming from works of art are frequently unique or extremely small, limitations can be due to different reasons, which frequently coexist, mainly: (1) the particles to be analyzed are too small; (2) the particles are too few; (3) the particles are intrinsically dispersed

in a complex texture and do not provide a recognizable signal, or they cannot be separated and concentrated; (4) chemistry does not allow discrimination between different minerals having similar composition; and (5) other technical difficulties in performing and/or interpreting analyses (for example, X-ray shielding caused by lead-based materials). Such restrictions can frequently be overcome by using the EBSD technique because the diffraction signal is produced by particles even smaller than 1 micron, which can be appropriately observed and identified by conventional SEM backscattering imaging.

Some limitations of this technique are commonly recognized and can be summarized as follows: The best rate of diffracted electrons is obtained for a particular beam/surface geometry so that the sample has to be tilted at nearly 70 degrees, placing the phosphor screen very close to the sample. Operating at a working distance usually in the range 5–25 mm, the possibility of collisions is strongly increased due to the reduced distance between the sample, phosphor screen, and other detectors.

Among other minor technical problems that can arise during the experiment, it is well known that the polishing of the specimen represents a decisive step in the preparation of samples. In fact, a perfectly smooth surface is needed to produce a pattern sufficiently sharp enough to be indexed, especially in the case of automated acquisition and indexing, so careful sample preparation is crucial to achieve successful EBSD analysis. Electro-polishing, and chemical and ion etching are good techniques used to remove any remnant deformation layers and surface irregularities, but for rock-like materials (mortar, stones, pottery, glass, etc.), sample preparation usually consists of many mechanical grinding and polishing steps of the sample surface. After mounting in epoxy resin, the sample is usually ground by means of a vertical diamond wheel, in order to obtain a rough flat surface, and then smoothed by an automated polisher. As grit-based polishing always introduces huge lattice distortion in the uppermost crystal surface, this damage must be definitely removed to obtain quality patterns. The first fine polishing is achieved by successively polishing using 6- to 1-micron-size diamond suspensions on silk cloths for a few minutes each.

Finally, the specimen is polished by means of a vibrating polisher with colloidal silica, for time periods that basically depend on the nature of the sample—ranging from a few minutes in the case of soft metals such as copper, to several hours for hard minerals like quartz and silicates in general.

With inhomogeneous materials, differences in strength between particles and the surrounding matrix could cause an imperfect polishing of some crystal surfaces. This happens, for example, in the case of mortars and plasters where hard mineral grains (quartz, silicates, etc.) are enveloped in a relatively softer carbonate matrix. Due to this difference in strength, during polishing, soft material tends to be mostly removed in respect to the harder grains that remain as reliefs on the surface. When the sample is tilted at a high angle, the surface topography enhances the interference with the incident beam, causing shadowing effects and electron charging.

Similar difficulties can occur in the study of alteration products caused by material deterioration or reaction rims grown during production processes (melting, precipitation, etc.) where softer substances are in close contact with harder ones.

In the frequent case of insulating materials, conductive materials such as carbon and gold can be sputtered or evaporated onto the sample to avoid charging effects. The coating should be as thin as possible, but sufficient to dissipate the electron charge on the surface without reducing the signal of diffracted electrons emerging from the sample. A range of 3–5 nm is generally acceptable for EBSD, although reasonable quality EBSD patterns have been obtained while operating in low-vacuum conditions without coating.

SEE ALSO: Archaeomineralogy; Diffraction; Electron Microscopy in Conservation; Instrumental Analysis of Lithics; Metallography; Pigment Alteration

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The Encyclopedia of Archaeological Sciences: Bridging Archaeological Scholarship and Science

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Archaeological investigations have become increasingly sophisticated in recent decades with the application of analytic methods to the study of past and present societies. The application of analytical methods to interpret material remains and to learn about human populations from the distant past to the present has encouraged the collaboration of archaeologists with scientists from a wide range of disciplines. The collaboration has resulted in numerous peer-reviewed publications, in new lectureships and professorships, in a wider range of undergraduate and postgraduate degree courses being offered, and even in dedicated funding by research entities.

However, learning about the compositional structure of archaeological materials or surveying sites with sophisticated tools requires a more rigorous interpretation of archaeological data: it involves reasoning with a theoretical background in a wide range of disciplines from the humanities and the social sciences. In an unprecedented effort, the Society for Archaeological Sciences (SAS) and Wiley Blackwell came together to provide the reader with an essential reference work from which to learn about the epistemic challenges behind the use of science and technology in the field and the laboratory, and to interpret social contexts and individual actions.

The Encyclopedia of Archaeological Sciences is a four-volume print and electronic multidisciplinary reference work, comprising more than 480 entries, written by more than 550 contributors from 47 countries. It covers essential content areas, offering a detailed

description of analytical methods and case studies through the many voices of archaeologists, heritage practitioners, and scientists around the world. How we reason with science and technology to learn about societies in the past and the present is what distinguishes this reference work of value to these professionals and students of archaeology and related disciplines. To support its aim, *The Encyclopedia of Archaeological Sciences* includes key theoretical concepts to provide evidence and solutions to approach the diversity and complexity of human societies through time. Therefore, scholars from the social sciences and the humanities have joined us in this venture, highlighting the value of archaeological data in providing innovative approaches and solutions to modern phenomena that are challenging our capacity to live on the planet.

Archaeological Sciences

Archaeology, defined generally as the study of societies in the past though the analysis and interpretation of material remains, is a discipline in which practice is entwined with the history of science. Many scholars have written about the history of archaeology, from Glyn Daniel (1981) to Bruce Trigger (2008) and Tim Murray and Christopher Evans (2008). All of them have inspired this brief history of the relationship between archaeology and science, resulting in the founding of archaeological sciences, a sub-discipline generally interested in the application of science, technology, engineering, and mathematical methods in archaeology, as expressed by Dr. Martín-Torres in this volume. In this overview of its history, I discuss the fact that this science-based archaeology is inspired by a theoretical background, and, as such, it is central to the formulation of new theories by providing insights to long-standing assumptions in archaeology (see Martín-Torres and Killick 2015).

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Archaeology, Science, and Philosophy

The scientific principles that established archaeology as a discipline in the nineteenth century may be traced to that moment in our history, back in the seventeenth century, when science replaced Biblical explanations through the works of Descartes, Bacon, Newton, Leibniz, Galileo, and John Locke. The “Age of Enlightenment,” as referred to by Immanuel Kant, was simply the period when the explanation of natural and social phenomena was based on human observation and experience. The search for explanations invited scholars, such as William Harvey and John Aubrey, to conduct explorations at Stonehenge and Avebury in England, respectively.

During the eighteenth century, human reasoning dominated many disciplines, including philosophy, mathematics, and astronomy, paving the way for the establishment of new fields of knowledge that incorporated earlier inventions, such as the microscope and the telescope, to fortify their observations. Knowing about the past was of great interest to monarchs and was also a means to gain fame and prestige. What could now be understood as “state-sponsored excavations” resulted in the exploration of Pompeii and Herculaneum, funded by Carlo di Borbone. In 1764, the advent of archaeology as a discipline was outlined in the publication *Geschichte der Kunst des Alterthums*, in which Johann Joachim Winckelman presented a systematic approach to the study of the past by separating and classifying Greek from Roman art at the end of the eighteenth century.

In the nineteenth century, explorers introduced a fundamental change to research practice by going into the “field.” Knowledge based on “fieldwork” was of ultimate importance to great explorers such as Alexander von Humboldt and Charles Robert Darwin. The five-year exploration of the Americas by Humboldt was not only crucial to the natural sciences, but also to archaeology and anthropology, as he recorded the antiquities of the New World and its people. “Fieldwork” observations were crucial to Lyell’s relative dating of geological strata, suggesting that upper soil horizons were newer than the lower ones. Lyell’s research introduced its first dating method to archaeology. In my own personal opinion, these centuries are unique in the sense that the natural

sciences and the humanities had never worked so closely together to expand human knowledge.

Throughout the nineteenth century, professional societies were established, and universities around the world began offering specialized degrees in a wide range of disciplines. Natural scientists advanced their observations by developing theories and methods based on laboratory practice. In fact, the Rathgen Research Laboratory, created in 1888, was the first of its kind to conduct chemical procedures for the preservation of objects housed at the Royal Museum in Berlin, now the *Altes Museum*. What an honor it is to have Dr. Stefan Simon, who was director of the “Rathgen Lab” between 2005 and 2014, as one of our contributors.

Darwin’s theory of evolution and its application to understanding societies were two essential principles guiding Augustus Pitt Rivers to create typological classifications to establish chronological sequences. His systematization of artifact studies, together with Mortimer Wheeler’s introduction of the grid system, set the basis for considering archaeology as a scientific activity.

During the twentieth century, quantum physics and the theory of relativity brought important changes to the construction of knowledge by investigating phenomena through observable, empirical, and measurable evidence from which theories can be extracted and tested with hypotheses. Archaeologists adopted these scientific principles, acknowledged as positivism, in the 1960s, after archaeological research moved away from a cultural historic approach, defining societies based on their ethnicity and material culture. The introduction of the electron microscope and the early definition of DNA are just a few examples of the new technologies and research that influenced archaeological research. However, one of the most important discoveries of great impact on archaeology after World War II was the introduction of radiocarbon dating by Willard Libby. In 1946, Libby proposed the dating of organic materials by measuring their content of carbon-14. Radiocarbon dating now uses other methods beyond measuring decay rate, explained here by Dr. Ramsey, Director of Oxford Radiocarbon Accelerator Unit.

From Archaeometry to Archaeological Sciences

In outlining the history of archaeology and science, Oxford University has played an important role. In 1958, Prof. Christopher Hawkes coined the term “Archaeometry” as the new title of the *Bulletin* published by the Research Laboratory of Archaeology and the History of Art at Oxford University, still published by Wiley Blackwell. The *Bulletin* described the applications of the physical sciences to the study of the past at this facility. Described in these pages by Prof. Michael Tite, “archaeometry” is now a more or less obsolete term, making reference to the study of artifacts and buried archaeological features by physical and dating methods. Still, the International Symposium on Archaeometry, owing its existence to Dr. Martin Aitken, who was also director of this lab and one of the greatest scholars archaeology has ever seen, uses this word. This international symposium began as a day meeting organized by Dr. Aitken back in 1962. The meeting became the “Symposium on Archaeometry and Archaeological Prospection” in 1969. In 1976, it changed its name to the “International Symposium on Archaeometry and Archaeological Prospection.” Since 1980, the International Symposium on Archaeometry has been a specialized forum for all those using scientific techniques for the extraction of archaeological and historical information.

The post-World War II era created a context that questioned the “philosophy” behind previous scientific practices, resulting in novel approaches involving the social sciences and the humanities. The “new philosophy of science” offered an interdisciplinary knowledge-trading zone between the natural and the social sciences that reached archaeology in the 1970s. Archaeology, a discipline then dedicated to the study of past “civilizations” through their material remains, became interested in learning about societies, entangled in a network of social, political, and economic variables. Archaeology required new tools and theoretical paradigms from other disciplines, including environmental sciences, biology, computing, and mathematics, to approach new questions—questions that archaeometric studies could not address entirely. Consequently, the word “archaeometry” does not express the

wide range of disciplines used in archaeological research today. Therefore, the term “archaeological sciences” is more appropriate to make reference to the application of science, technology, engineering, and mathematical methods in archaeology, as discussed in this reference work by Dr. Martín-Torres.

The expansion of scientific techniques applied to archaeological research laid the groundwork for the organization of the Society for Archaeological Sciences (SAS) during the International Symposium on Archaeometry and Archaeological Prospection that took place at the University of Pennsylvania in Philadelphia in 1977 (Sternberg 2014). The SAS, as a professional society, is interested in advancing archaeological sciences and promoting an active program encouraging interdisciplinary research in archaeology (Sternberg 2014). Since 1977, the SAS has published a *Newsletter*, now the *Bulletin*, as part of its strategies for communicating with its membership. Since 1982, the SAS has sponsored archaeological science sessions at the Society for American Archaeology. The SAS is committed to rewarding outstanding students through the R. E. Taylor Poster Award and supporting their research activities through the SAS Student Research International Travel Award. The SAS is one of the few professional organizations in archaeology whose leadership has been in the hands of foreign scholars, such as myself.

For the SAS, archaeological sciences embrace much more than the physical, biological, chemical, and environmental sciences, by studying organic and inorganic archaeological remains and their spatial location, aided by computing and mathematics to process, analyze, model, and predict derived data. The close engagement with scientific disciplines and correlated methods is simply to learn about human societies in the past and in the present. In fact, *The Encyclopedia of Archaeological Sciences* was designed to inform analytical methods with a larger corpus of interdisciplinary theories to understand human societies in the past and the present. Conceptual frameworks from other domains in anthropology, ethics, economics, history, political science, and aesthetics, to mention just a few, interact throughout this reference work, with the use of science and technology to answer questions about the past and the present.

The Encyclopedia of Archaeological Sciences: An Introduction

In 2011, as I ended my term as President of the SAS, Wiley Blackwell supported my interest in developing *The Encyclopedia of Archaeological Sciences* (EAS), a reference work for those interested in learning about the application of science and technology in archaeology. In heading this project, I envisioned an encyclopedia of archaeological sciences establishing a dialogue between archaeological theorists and archaeological scientists, given the unnecessary and unproductive existing division between these “two cultures,” which Martínón-Torres and Killick (2015) have discussed so eloquently.

In building the contents of the EAS, I invited 10 international and well-recognized scholars, who have different professional backgrounds, to manage key areas and to provide the reader with the scientific principles and techniques to understand the lives of those who have come before us, supported by theoretical approaches from the social sciences and the humanities, to allow for a more rigorous interpretation of archaeological data. In asking myself about the future of archaeological data, part of the vision of the EAS had to include key areas showing us how to take care of our past and to find good practices to preserve our past for future generations. In my capacity as a Humboldt Foundation fellow and prize awardee, I have met scholars from a wide range of disciplines through multidisciplinary international forums, in which we all have demonstrated the value of our disciplines and of facing, together, current phenomena challenging our living in this world. The EAS aims to demonstrate, to professionals and practitioners from those disciplines from which we have borrowed, what archaeology has to offer in analyzing and solving current natural and social phenomena. The contents of the EAS, therefore, lay bare my concerns.

The Structure of The Encyclopedia of Archaeological Sciences

Concerned about the growing educational and professional needs in the field, the EAS was divided into 11 essential and interrelated content areas or sections, from which headwords were

developed by the associate editors. Together with Dr. Gilberto Artioli, we defined headwords describing the fundamentals of scientific principles and techniques that were presently used in archaeology or could be of use to future research. Therefore, the user of the EAS will be able to learn the workings of a specific technique in great detail. The section provides a background for learning about the application of these techniques in the field and the laboratory for analytical or conservation purposes. In working together with Dr. Christian Wells, we identified those techniques that help professionals survey and excavate a terrestrial or underwater site. In dating archaeological findings, Dr. Josep Parés followed simple questions to build his section. How do we construct time in archaeology and which techniques are of use to date archaeological findings? How we study and characterize archaeological materials and how artifacts were made are some of the questions that Dr. Luis Barba followed to build a section that could be the basis for understanding the technology behind the making of an object and the reasons why an artifact was made. The question of who made those artifacts required an understanding of people in the past. In approaching how to study people in the past, Dr. Lori Wright and Dr. Kristin Hoffmeister developed a section to help us define population genetics, age, and gender, and even their diet and mobility. Mrs. Gill Campbell, through her section, has supported our interest in reconstructing people's natural living environment and in understanding the subsistence and economic activities that formed part of their landscape.

Working with archaeological data to interpret past societies involves reasoning, not only based on theories; it involves mathematics, logic, statistics, and modeling. How to construe archaeological data as evidence of past societies requires well-structured research, based on a hypothesis and an understanding of the validity and reliability of our data. Which kinds of techniques or instruments can help us compute these data? These questions, developed by our contributors, have the intention of pursuing social interpretations from numbers. Encouraging social interpretations of instrumental results involves theoretical approaches that Dr. Julian Thomas has carefully selected to help us reason

with science, inviting us to rethink how we build our knowledge about the past from the present.

How to visualize and analyze archaeological data has been the task of Dr. Christopher Dore, who has brought together a group of scholars sharing their expertise in creating images through analytical instruments, augmented reality, or 3D imaging, along with the use of information and communication technologies (ICT) to facilitate archaeological research and disseminate its results. How to preserve the past is a key concern of the EAS. Conservation is the obvious answer that Dr. Ioanna Kakoulli provides, by sharing with us those techniques and best practices to help us extend the life of excavated or stored artifacts through the words of her contributors. What to preserve and how we connect with the past are key concerns approached by Dr. Graham Fairclough and his contributors. The value of heritage to society is included in the EAS, introducing the reader to different heritage management preservation strategies.

The Encyclopedia of Archaeological Sciences is simply the result of the Associate Editors and its contributors, who kindly collaborated with us and helped us build the headwords that make this reference work possible. Indeed, we need to accept that we might be missing some key concepts. Like any long-term project, we added new key concepts, while we had to drop others for various reasons. The Associate Editor and the Editor-in-Chief, working hand in hand with the contributor, reviewed each submission. In some cases, external peer-reviewers revised some of the entries for final acceptance.

I asked the Associate Editors to invite well-known scholars to write the entries. To me personally, it was very important to invite those scholars who do not publish regularly in English and, therefore, are less known to our community. In addition, I wanted to invite new talents and to give them the opportunity to publish along with our well-established scholars. In the end, we recruited over 550 contributors from 47 countries, not all English native speakers, including myself. Their participation has given us the opportunity to include multiple perspectives and case studies from around the world. I could not be more indebted to all of our participants and our editorial staff for their willingness to collaborate in our project.

How to Use *The Encyclopedia of Archaeological Sciences*

The EAS aims to be a basic source for archaeological research through a compendium of terms, covering the specifics of a technique, how the technique is used in archaeology, and how we can construe its results as evidence to learn about societies in the past or even in the present. This may be achieved by searching terms linked across areas of interest. In addition, each term, generally, has a further reading section to expand coverage, in case the reader would like to know more about a particular area. Given the nature and range of its contents, the EAS stands as a reference for the expert who wants a quick source of details about a specific technique or theory.

In building the contents of the EAS, I envisioned its use in the classroom and as an aid in building lesson plans. Therefore, I encourage those teaching courses in a diverse set of classrooms, not only those related to archaeology or anthropology, to use the EAS as a source for students to learn about a term and to encourage discussion surrounding its application and to learn about societies in the past and in the present.

Why Now is the Perfect Time to Publish an Encyclopedia of Archaeological Sciences

In the twenty-first century, archaeology can no longer be conceived without science, or at least, this is what our generation learned back in the 1980s, when many of us were trained to combine anthropology, archaeology, materials sciences, and spatial analysis to approach societies in the past. Many scholars from this interdisciplinary generation have extended archaeological practice to those working with environmental and social sustainability and to approach global challenges, such as climate change, ocean health, poverty, food security, energy, even human rights and democracy. Until very recently, such collaboration was a source of optimism for our collective future.

Across the globe, scientists have detected a decline of trust in science and scholarship, given the unsubstantiated assertions released through

public discourse and disseminated by mass media. In this setting, we should ask ourselves why unsubstantiated assertions are gaining more attention from the public than evidence-based argumentation. The publication of *The Encyclopedia of Archaeological Sciences* comes at a time when we need to acknowledge our shared responsibility to society and analyze the ways we communicate our research results to the average citizen, if we wish to reverse this situation. The EAS has built a vibrant international community standing up strongly for science, the social sciences, and the humanities, regardless of the political winds trying to set up barriers between countries. The EAS advocates for science, through the diversity of voices unified here, as a building force, contributing to world prosperity and peace.

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Gas Chromatography-Mass Spectrometry (GC-MS)

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Gas chromatography-mass spectrometry (GC-MS) is a hyphenated technique: a combination of two techniques used to study and characterize mixtures of organic molecules. Gas chromatography separates the organic molecules of a mixture, and mass spectrometry characterizes each molecule. By combining the two techniques, organic samples can be both qualitatively and quantitatively evaluated.

GC-MS is one of the preferred analytical approaches used to characterize organic substances and materials from archaeological findings, as confirmed by a number of successful applications and case studies reported in the literature (Colombini and Modugno 2009; Colombini et al. 2010; Colombini, Modugno, and Ribechini 2012; Bonaduce et al. 2016). GC-MS is unique in its ability to yield complete chemical structure assignments and to identify a great variety of organic substances, thus enabling characterizations at a molecular level to be carried out. The most common application of GC-MS in archaeology is the identification of molecules that behave as markers (Colombini, Modugno, and Ribechini 2005; Evershed 2008). The key idea behind the concept of *biomolecular markers* in archaeology is that the carbon skeleton of some organic molecules remains fundamentally unchanged during aging, while the main transformations affect the functional groups. By identifying the structure of the organic components of the sample (or *analytes*), it is possible to establish a “product–precursor” correlation and hypothesize the original molecular structures. If these molecules are unique to a certain material, they can then be used as *biomolecular markers*

to establish the origin of the natural substances present in the sample, and to understand the natural and artificial alteration processes that modified the materials.

Gas chromatography (GC) is an instrumental technique that allows the separation of the different components of a sample (see CHROMATOGRAPHIC TECHNIQUES IN CONSERVATION AND CHROMATOGRAPHY AND ARCHAEOLOGICAL MATERIALS ANALYSIS). The molecules are carried, or *eluted*, by a gas (typically He, N₂ or H₂) through a capillary column. Modern GC columns are typically 15–60 meters long, with a submillimetric diameter. The external part of the column, which is flexible and inert, is usually made of fused silica. The inner wall, which is in contact with the carrier gas and the sample molecules, is coated with a uniform film of polymer, which can be functionalized to increase the separation efficiency towards specific classes of compounds. The carrier gas is also called the “mobile phase”, while the internal coating polymer is called the “stationary phase”.

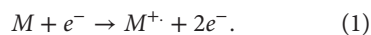
GC analyses require the samples to be in the gaseous phase. The introduction of a sample (in liquid or gaseous phase) into the GC instrument is called *injection*, since it is usually performed with a syringe. The *injector* connects the entrance valve with the chromatographic column. This is also the place where the volatilization of liquid samples takes place. Injection is a very delicate part of the GC analysis. GC injectors are equipped with a *gas-split* system, which reduces the amount of injected sample that actually reaches the column.

The *split ratio* is a very important parameter that indicates by how much the sample quantity will be reduced. Split ratios can be as high as 100:1 (i.e., only 1 percent of the injected sample will be analyzed). A high split ratio is particularly useful when dealing with highly concentrated samples, for which even the smallest injected quantities are excessive. When dealing with very diluted samples, on the other hand, the gas splitter can be shut off, and the injection mode is called *splitless*.

Inside the column, the molecules are separated according to their volatility. Lighter molecules,

with a lower boiling point and a greater tendency to remain in the gas phase, will quickly reach the end of the column, while larger molecules, with higher boiling points, will require more time. Since the volatility of a molecule is directly correlated with the temperature, the column is coiled inside an oven. The temperature is accurately monitored during the analysis, and is usually increased over time (usually with rates between 5 and 20°C min⁻¹) in order to increase the volatility of the heavier molecules. Temperatures in the range 50–300°C are typically used.

Once the molecules are separated by GC, they are identified using a mass spectrometer (MS) (see MASS SPECTROMETRY (MS)), which is directly connected to the end of the column. Inside the MS, the molecules are converted into ions in gaseous phase by ionization techniques, the most common being collision with a high-energy electron beam generated by a metal wire held normally at 70 eV. A molecular ion is initially generated by removing one electron from the molecule, as shown in reaction (1). This molecular ion is energetically unstable, and undergoes fragmentation and rearrangement reactions to generate smaller ion fragments.



Inside the mass spectrometer, the ions are separated according to their *mass-to-charge ratio* (*m/z*) values. The piece of instrument that separates the ions is called a *mass analyzer*. There are several types of mass analyzer, based on different principles and with varying performances. The most common mass analyzers are quadrupoles (Q) and ionic traps (IT), which analyze the ions by applying electromagnetic fields. Once the ions have been separated by the mass analyzer, their amount is calculated by a detector. The detector, typically an electron multiplier, records the ionic current produced when an ion passes by or hits a surface.

The final result of the analysis is a *chromatogram*, which is a graph that shows the intensity of the ionic signal (the current) as a function of time. A mass spectrometer can work both in TIC (total ion current) and SIM (single ion monitoring) acquisition modes. When TIC mode (known also as *full scan* mode) is used, a range of *m/z* values is monitored and acquired. A typical mass

scan range covers from 50 to 700 *m/z* values. In SIM mode, only a few *m/z* values, typically two to four, are acquired. The use of SIM improves selectivity and sensitivity, and consequently the SIM mode is frequently used for quantitative GC-MS analyses. On the other hand, the TIC mode is preferred for qualitative analyses and for identifying unknown compounds. The type and number of ion fragments obtained during ionization are reproducible and characteristic of each molecule, and thus a mass spectrum can be used as a *fingerprint* for its identification. In addition, the area of the chromatographic peak is directly proportional to the concentration of the corresponding species in the sample, thus enabling a quantitation of the sample components to be carried out. The proportionality constant for the conversion is usually determined by performing a GC-MS analysis of a sample in which the compound is present at a known concentration.

In the archaeological field, GC-MS has been used to characterize different types of samples, such as resins, lipids, waxes, and proteins (Bonaduce et al. 2016; Colombini and Modugno 2009; Colombini et al. 2010, 2012) (see PIGMENTS AND BINDERS). A number of challenges must be overcome when searching for markers. For example, biomarkers can be trapped inside the matrix by physical and/or chemical interactions with the other constituents of the sample. Moreover, some of these markers cannot be directly analyzed with GC-MS, since their dimensions and chemical structures make them nonvolatile. A pre-treatment of the sample is thus required in order to isolate the compounds of interest from the matrix and to transform them into species that are suitable for GC-MS analysis.

Isolation techniques include: (1) *liquid-phase extraction*, which can be used to separate compounds with significantly different polarities; (2) *sonication*, which can overcome the physical trapping of the molecules by decomposing the matrix and improving the efficiency of liquid extraction; and (3) *solid-phase extraction*, which can also be used to pre-concentrate the analytes.

Transformation techniques include:

1. *Hydrolysis*, which is the breaking of chemical bonds by reaction with a water molecule.

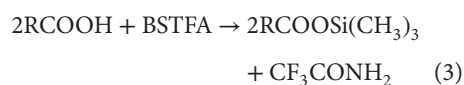
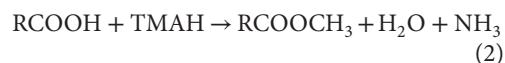
Hydrolysis can be used to decompose polymeric species such as proteins and polysaccharides (present in animal proteins and plant gums as pigment binders; see PIGMENTS AND BINDERS) into their monomers, as well as to obtain free fatty acids from mono-, di- and triglycerides (the main constituents of acylglycerolipids such as plant oils).

2. *Derivatization*, which is the reduction of the polarity of molecules by modifying their functional groups. This is done by reaction of the analytes with a *derivatizing agent*, which increases their volatility. Derivatization typically affects functional groups that have mobile hydrogen atoms such as hydroxyls and carboxyls, since they are the most polar.

Table 1 lists the pre-treatment steps usually required for the analysis of organic species commonly found in archaeological samples. The table also shows the molecules that are obtained at the end of the pre-treatment and are detected by GC-MS. A derivatization step is required in all cases, since hydroxyl and carboxyl groups can be found in all analytes. Polar groups are known to interact with the solid phase of the column, generating broad and poorly resolved peaks in the chromatograms. Derivatization thus also improves the quality of the chromatograms.

Typical derivatization reactions are methylation and silylation. With methylation, mobile hydrogens are replaced with methyl groups. This reaction is usually performed with tetramethylammonium hydroxide (TMAH). With

silylation, mobile hydrogens are replaced with silicon-based groups such as trimethylsilyl ($\text{Si}(\text{CH}_3)_3$). This reaction is usually performed with bis-trimethylsilyltrifluoroacetamide (BSTFA). Examples of methylation and silylation reactions of carboxylic groups are shown in reactions (2) and (3), respectively.



A practical case study is now presented for the data and results obtained in the GC-MS analysis of a sample collected from a Roman amphora found in an archaeological site where several Roman ships were uncovered (Pisa, Italy). In Roman times, ceramic amphorae were usually coated with resinous substances in order to make them waterproof. Among the various substances that can be found in archaeological samples, resins are of particular interest, due both to their wide use as a multifunctional material, and their stability toward aging. The main chemical components of resinous materials are terpenes, which comprise a vast family of compounds originating from the combination of two or more isoprene molecules. Pine resin was a very common material in ancient times, and was frequently used for the production of pitch (Colombini et al. 2003, 2005; Duce et al. 2015). The most abundant terpene in pine resin is *abietic acid*, whose structure is shown in Figure 1a. When

Table 1 Pre-treatment steps and expected analytes for the GC-MS analysis of organic materials of archaeological interest.

<i>Material</i>	<i>Pre-treatment</i>	<i>GC-MS analytes</i>
Proteins	Isolation from matrix, hydrolysis, derivatization	Amino acids
Polysaccharides	Isolation from matrix, hydrolysis, derivatization	Monosaccharides
Acyl-glycerolipids	Saponification, liquid-phase extraction, derivatization	Fatty acids
Waxy lipids	Saponification, liquid-phase extraction, derivatization	Long chain alcohols, hydrocarbons, fatty acids
Resins, pitch and tar	Saponification, liquid-phase extraction, derivatization	Terpenes

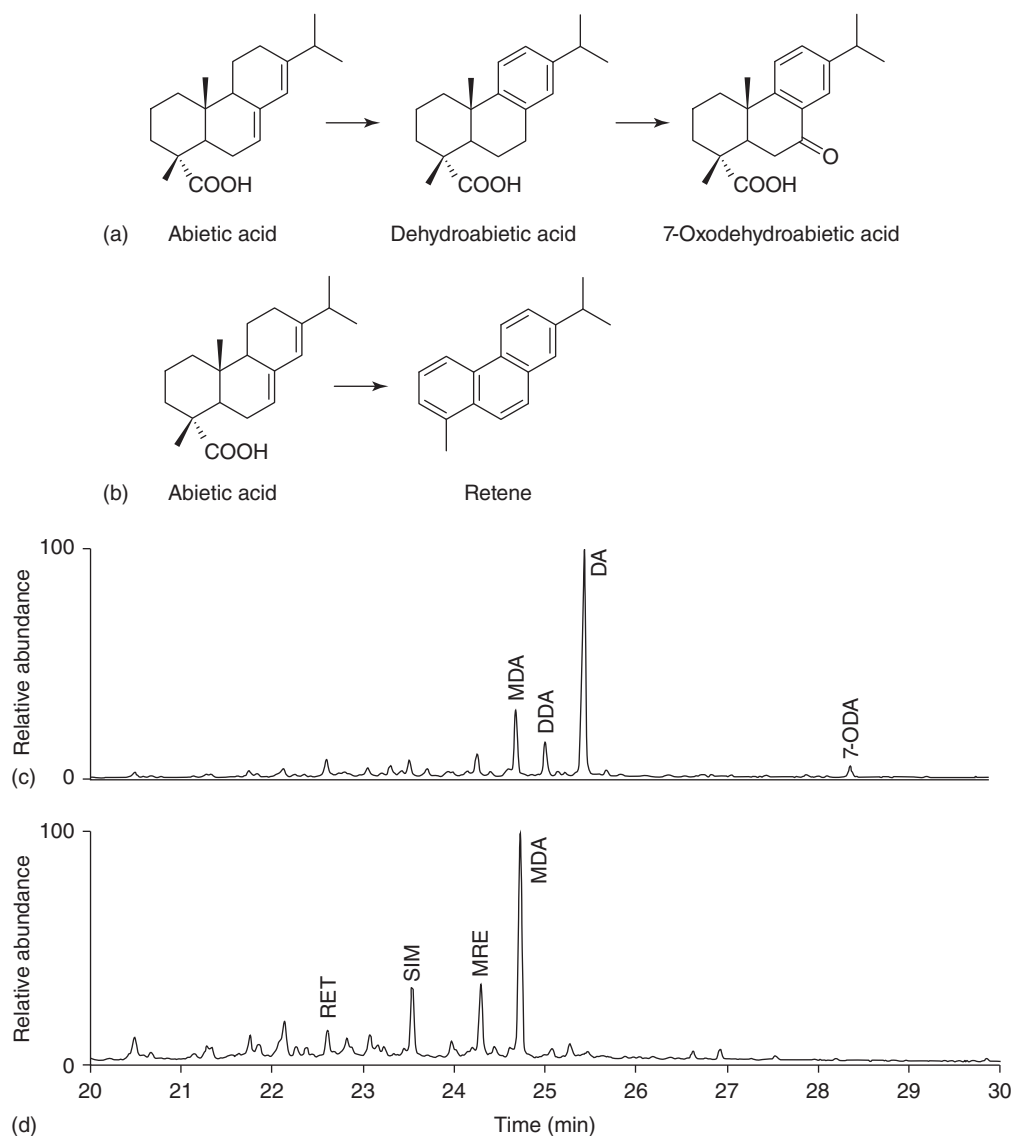


Figure 1 Reaction schemes for the oxidation (a) and the heating (b) of abietic acid. TIC chromatograms of the acidic (c) and neutral (bottom) fractions (d) of an archaeological pine pitch sample. MDA, methyldehydroabietate; DDA, didydroabietic acid; DA, dehydroabietic acid; 7-ODA, 7-oxodehydroabietic acid; RET, retene; SIM, simonellite; MRE, methylretene.

pine resin is subject to aging, abietic acid undergoes oxidation reactions, leading to the formation of dehydroabietic and 7-oxodehydroabietic acid. When the resin is heated to generate pitch, on the other hand, abietic acid loses the carboxyl group and undergoes a series of dehydrogenation reactions, producing norabietatriene and retene (Figure 1b).

The different products of these two reaction pathways can be used to distinguish archaeological samples containing pine pitch from those containing pine resins. This is done by performing a liquid-phase extraction to separate the neutral components (norabietatriene and retene) from the acid ones (abietic acid, dehydroabietic acid, 7-oxodehydroabietic acid).

The two fractions are then analyzed separately by GC-MS. If the neutral compounds are present, the archaeological sample probably contained pitch, while if they are absent, it probably contained untreated resin.

Figures 1c and d show the chromatograms of a sample collected from a Roman amphora found at the site in Pisa. The chromatogram of the acidic fraction shows clear peaks corresponding to dehydroabietic and 7-oxodehydroabietic acid, as well as a signal for didehydroabietic acid, which is an intermediate species between the two. The neutral fraction, on the other hand, shows signals corresponding to retene, methylretene and simonellite (an isomer of methylretene). The presence of methyldehydroabietate is particularly interesting. This compound originates when pine resin is heated in the presence of wood. From these data, we can hypothesize that the amphora probably contained pine pitch, and that this pitch was produced by directly heating the resin on the wood.

A separate discussion is required for a specific pre-treatment technique: *pyrolysis*. Analytical pyrolysis is the thermal degradation (generally in a temperature range between 300 and 800°C) of a sample into molecules (pyrolysis products or fragments) of lower mass, yet large enough to provide analytical information on the original sample. Given that these smaller compounds are more volatile, they can be analyzed by GC-MS. The pool of pyrolysis products observed then provides a fingerprint of a particular sample, in terms of both fragment nature and relative distribution. The data output of the analysis is a *pyrogram*. Modern analytical pyrolysis instruments provide a good reproducibility of the results. One of the main advantages of pyrolysis is that it requires no sample pre-treatment. Solid or liquid samples can be placed directly inside the pyrolyzer, the chamber in which the pyrolysis takes place. The pyrolyzer is usually equipped with a needle directly inserted into the GC injector, and the whole technique is known as Py-GC/MS.

Pyrolysis thus has a similar purpose to hydrolysis, but is preferred when dealing with very stable compounds, especially natural polymers, which are hard to pre-treat by wet chemical methods before GC-MS analysis. Classic examples of such compounds are *fossil resins* such as ambers and

lignin, one of the major components of wood. Lignin is more stable towards aging than other wood components, and therefore its analysis is of great interest in the archaeological field. Lignin is a polymeric compound, but its chemical bonds are very stable and hard to break using hydrolysis. Pyrolysis is a very effective way to analyze wood samples with GC-MS (Colombini et al. 2012; Lucejko et al. 2015).

SEE ALSO: Chromatographic Techniques in Conservation; Chromatography and Archaeological Materials Analysis; Mass Spectrometry (MS); Pigments and Binders

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Geoarchaeology

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Introduction: Geoarchaeology is Archaeology

Two recent publications (Hill and Rapp 2010; Hill 2017) have thoroughly and exhaustively described the history of geoarchaeology. The latter will not therefore be recalled in detail here. Still, a brief focus on the initial or “formative” stage of the collaboration between earth sciences and archaeology, around the middle of the nineteenth century, will be provided. This phase can be summarized in two main epistemological trajectories. On one side, there is the research concerning the “antiquity of man.” On the other side, the circumstances that led to the “birth of interdisciplinary archaeology.” More than archaeologists, it was early “earth scientists” or “natural scientists” such as C. Lyell, J. Boucher de Perthes, and W. Pengelly who dealt with the issue of the antiquity of man. These scholars were primarily interested in demonstrating the unequivocal association of remains of long-extinct fauna with objects produced by man. To achieve this incontrovertible and scientific evidence, *stratigraphy*, was employed as key method, and the *stratigraphic* excavation of Brixham Cave (Devon, UK) by Pengelly in 1858–59 led to the general acceptance—also favored by the publication in 1859 of Darwin’s *On the Origin of Species*—that indeed man coexisted with (Pleistocene) extinct fauna and therefore existed prior to the biblical deluge. The close ties between geology and cave and rock shelter archaeology or, more broadly, Paleolithic archaeology, begun here. This de facto “geoarchaeological” approach remained rather self-contained throughout the successive developments and involutions of archaeological methodologies and theories. This owes mainly to the low “signal to noise ratio” of Paleolithic contexts, where the anthropic signal is diluted

within a preponderant set of processes and features of natural origin, and where researchers face long timescales and a succession of different paleoenvironments.

The excavation of coastal shell middens containing ancient artifacts in southern Scandinavia since 1848, carried out by archaeologist J. J. Worsaae, paleontologist J. Steenstrup, and geologist J. G. Forchhammer, is seen as the first episode in interdisciplinary archaeology. Such excavations led to the understanding that the middens were not natural formations but in fact the remains of human occupation, and permitted also the refinement of Thomsen’s “three-age system.” Slightly afterwards, the discovery of pile dwellings in Switzerland, due to an exceptional lowstand of lake levels in 1853, promoted the collaboration between archaeologists and natural scientists. Not just geologists, but also plant specialists begun to be involved from this point on, as waterlogged conditions allowed for the perfect preservation of wood and botanical remains (i.e., pollen, fruits, seeds). The discovery of Swiss pile dwellings promoted the collaboration between earth scientists and archaeologists also in Italy as early as 1861, a circumstance overlooked in most accounts of the birth of interdisciplinary archaeology. The work of geologist B. Gastaldi, naturalist B. Strobel, and archaeologist L. Pigorini on pile dwellings and Bronze Age settlements in north Italy (and before them of geologists G. Scarabelli and F. Stoppani) is remarkable.

Differently from “architectural” or “antiquarian archaeology,” this new “scientific archaeology” (Trigger 1989; see *ARCHAEOLOGY*) faced the *necessity* of resorting to geology and natural sciences. The archaeological objects and behaviors scholars sought were in fact deeply entangled in natural deposits, processes, and features. In this framework, the role of geology-derived *stratigraphy* was again crucial. It permitted objects to be ascribed to layers (thus enabling seriation after Thomsen’s system), to carefully record the sequences being excavated, to correlate sites and, most importantly, it constituted a communal reference point for the different specialists to interact.

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“Scientific archaeology” has therefore shared a set of concepts with geology since its very early development. Amid these concepts a key role is played by the laws of stratigraphy, formulated by N. Steno and J. Hutton in the 1600s and 1700s respectively, which, together with uniformitarianism, constitute two of the building blocks of modern geology. Based on this, the search for a definition of what geoarchaeology is can be avoided, stating more simply that geoarchaeology *is*, in fact, just archaeology. Geological principles have been at the very core of “scientific” or “modern” (or, at the very least, “stratigraphic”) archaeology’s development as opposed to other external scientific disciplines whose methods developed independently from archaeology and were then applied to it as “ancillary techniques.”

A matter of scales

Quoting the words of K. W. Butzer, who first crystallized the term “geoarchaeology” in 1973 (Hill and Rapp 2010; Hill 2017), “it [...] serves no practical purpose to seek logical, unifying structures or categories for what geoarchaeologists do” (Butzer 2008, 403). The fact is that, owing to the strong bonds that connect earth sciences and scientific archaeology since its very beginning (see before), geoarchaeologists deal with a wide plethora of aspects that are relevant to archaeological research. Yet, a characteristic common to all such aspects is the multiscale approach of geoarchaeology (see Goldberg and Macphail 2006; Butzer 2008). Surveying the distribution of a series of sites across a whole region or interpreting a X-ray diffractogram obtained from a few sand grains should be viewed as a movement along a continuum of information, from a broad to a very detailed level of observation. Such a continuum begins with the knowledge of the wider geological and geomorphological context in which a site or a study area is set, indicatively at scales of 1:100,000, 1:250,000 or even smaller. This is also referred to as the “macro-scale” (Butzer 2008). Information at this scale is normally obtained through the study of cartography (geological, geomorphological, topographic, soil, ancient maps) and remotely sensed data (aerial photos, satellite imagery, DEM,

LiDAR, processed images, etc.; see AIRBORNE REMOTE SENSING), when these are available, or by geological survey when preexisting data are unavailable or inaccessible. Without a clear cut between the macro-scale and the meso-scale discussed below, geoarchaeology is often concerned with the use of archaeological sites, artifacts, or geogenic materials (e.g., tephra; see TEPHRA AND VOLCANIC ASH ANALYSIS) to date geological events, and, conversely with the evaluations of their impact on past human groups or societies or their effects on site preservation. Such geological events can be volcanic eruptions, river avulsion, aggradation and downcutting, intervals of stability with soil formation, and so forth. The list also includes the impact that seismic activity and other structure-related processes (e.g., subsidence and consequent submergence of coastal sites, tsunami inundations, uplift along faults) had on past societies. These constitute the focus of archaeoseismology (see ARCHAEOSEISMOLOGY). Activity of faults is also of interest to geoarchaeologists facing the study of very long timespans, where dislocation of layers and significant alteration of the original topography might have taken place (e.g., Olduvai Gorge, Tanzania).

Paleoenvironmental reconstruction (see PALEOENVIRONMENTAL RECONSTRUCTION), one of the main fields of application of geoarchaeology, encompasses the analysis of litho- and biostratigraphic sequences and makes large use of absolute dating methods. Paleoenvironmental reconstruction might be based upon many very specific, local, or site-scale observations, but normally produces a regional or supraregional picture, comprising for example, climate changes, sea level variations, glaciers advance or retreat, evolution of estuarine environments or shorelines, desert areas dynamics. These past environmental or paleogeographical changes are relevant for archaeology as they are evaluated in terms of population dynamics and human adaptive responses.

Lastly, as geological maps represent the distribution and age of lithotypes in a given area, they are used for studies of provenance and sourcing of rock materials used for artifacts (chert, obsidian, flint clay, volcanic lithics, etc.) or for construction. Provenance and sourcing are determined by comparison of artifacts’ composition

with the lithotypes present in the area, by means of methods such as thin section petrography and X-ray techniques, among others. The geological composition of an area also influences the composition of the sediments that formed upon weathering and were eventually eroded and redeposited. The information on local sediments' composition is used in pottery studies (see *ELEMENTAL ANALYSIS OF POTTERY*) aimed at ascertaining the sourcing of mineral temper or of clays, or at identifying the origin of pottery (i.e., locally produced vs. allochthonous or imported ware).

Advancing towards a more detailed level of observation along the continuum of scales, the geomorphic unit(s) of interest, such as "floodplain," "dune system," "alluvial terrace," and so on should be defined. This more immediate background to the site or study area greatly influences the sedimentary dynamics that can predate human occupation (hence forming the "natural substrate" to it), interact with it (causing intermittent or discrete occupations) or postdate it (burial conditions). Of crucial importance is the distinction between areas of active and areas of inactive sedimentation. A site set on a geomorphic unit where sedimentation is inactive, as for example a relict alluvial terrace, will be subject to soil formation, with processes such as bioturbation and oxidation homogenizing and altering the archaeological deposits. Here, moreover, the stratigraphic sequences will be condensed, that is, there will be no sediments or soils formed thereon separating successive occupation episodes. Erosion, agricultural impact, and construction work will have a more severe impact on shallowly buried or, worse, surficial deposits. On the other hand, the stratigraphic sequence of sites located in areas with active sedimentation, such as a floodplain, will suffer less from soil mixing and consist of discrete occupations. Deeper burial might also result in the avoidance of later anthropic impacts, and the presence of a groundwater table could favor preservation of organics. Nevertheless, active sedimentation might imply strong erosion and total loss of archaeological deposits. Cores or hand auger observations in the near-site can augment the information at the meso-scale providing quick access to the buried record. Sedimentation and erosion can be triggered by

supraregional factors such as climate change or tectonics, but human impact on the environment often plays a role. This is the case for example, when vegetation clearance and agricultural practices along slopes results in the erosion of topsoil and in the deposition of colluvium (see French 2003). The concepts and analytical methods of pedology, the science studying soils, are often applied when reconstructing ancient land use. The latter encompasses practices such as deforestation (e.g., uprooting of trees and slash-and-burn), secondary clearance, manuring and soil amelioration, irrigation, tillage, terracing, and so on. These all alter profoundly the original environment around a site and leave traces in the soil-sedimentary record. Pedology can be also used to perform land evaluation, the determination of the suitability of ancient soils for specific land utilization types, such as the growth of certain crops or their use as pasture. The potential of pedology in geoarchaeology relies also on the fact that soil properties can change over very short distances, thus varying at a scale similar to the meso- or site-scale (see below). Soils form in response to a series of "soil forming factors," namely climate, organisms (including humans), relief, parent material, and time (known as "Jenny's equation"—quoted also in Hill and Rapp 2010, 3009). As these factors are recorded in soils, their role in the reconstruction of environmental and anthropic dynamics in a site and in its surroundings is paramount.

At the end of the continuum, the geoarchaeologist works at the site or "intra-site" scale. Here the focus can be on a group of stratigraphic units (with or without intercalated soils), on a single unit or soil horizon, on a specific anthropic feature (a fireplace, a pit, a floor, etc.), or natural characteristic (a mottle, a nodule, a biogallery) or on a single eco- or artifact. On site, the geoarchaeologist might be asked to discriminate between units of natural versus anthropic origin, to do correlations within the site and outside of it in the surrounding landscape, to collect samples for detailed stratigraphic studies (e.g., by means of soil micromorphology; see *MICROMORPHOLOGY*) or for other specialists. By working on site during the excavation, the geoarchaeologist will be able to choose the analytical techniques and to design a sampling strategy aimed at answering appropriate and relevant

archaeological questions. The greatest possible integration between different disciplines will be facilitated by knowledge of the stratigraphy of the site. Besides sampling, a great deal of work consists in describing lithostratigraphic units or soil horizons. Descriptions normally make use of a standard terminology, agreed upon at the national or international level, thus facilitating the presentation of data and communication with other specialists. Standard descriptive terminologies in sedimentology or pedology obviate archaeology's lack of specific stratigraphic nomenclature (notwithstanding the efforts of some authors in the 1980s and 1990s to create one).

One of the main tasks of the geoarchaeologist working at the site-scale is to reconstruct site formation processes, sometimes referred to as "formation processes of the archaeological record" (Schiffer 1987). In Schiffer's view formation processes are the link between the behaviors (what archaeologists aim at reconstructing) and the deposit (what archaeologists excavate). This basically means that deciphering formation processes implies disentangling all the processes, human (or behavioral or cultural) and natural, whose interactions shaped the deposit, that is, the artifacts, the biofacts, and the sedimentary matrix around them. Particular attention is given to "post-depositional processes," and "taphonomy" (see TAPHONOMY)—a term derived from paleontology indicating "the inputs, processes, and filters that transform a living community to a death assemblage and ultimately a fossil palimpsest" (definition by Butzer 2008, 404)—is often used. Site formation studies often benefit of the high resolution of the micromorphological study of thin sections, which allows observing artifacts and biofacts together with the sediments encasing them as they occur in the deposit (see Nicosia and Stoops 2017). In this approach the undisturbed sedimentary matrix provides the fundamental "context" to biofacts and artifacts (Goldberg and Berna 2010).

It is at the site-scale that probably the approaches of the geoarchaeologist and of a standard geologist differ the most. Here, in fact, one has to face the fact that the stratigraphic sequence of an archaeological site "largely reflects the historical and social particularities of the people who created it" (Lucas 2012, 89). Moreover, the site-scale is peculiar to archaeological contexts,

where relevant variations in color or texture can happen in a few centimeters, a circumstance which makes archaeological field stratigraphy in itself a form of "micro-stratigraphy" when compared to the scale of geological stratigraphy.

Perspectives

If really "geoarchaeology is archaeology," why then do many excavations still lack any geoarchaeological component and why, compared to the amount of archaeologists, are geoarchaeologists so few? One possible answer is that archaeologists receive little, if any, courses in disciplines of geosciences relevant to archaeology (e.g., geomorphology, sedimentology, pedology, etc.—see Goldberg and Macphail 2006; Goldberg 2008). This is rather absurd if we consider that exactly because *stratigraphy* is at the very core of scientific archaeology, a large part of what archaeologists do during excavation is observing, labeling, grouping, and correlating volumes of sediments or soil, ultimately producing a stratigraphic sequence. Conversely, also geologists receive little or no training in archaeology at university. Often times they encounter difficulties in understanding the scale and the subtleties of archaeological features and the type of information relevant for archaeological research. The geoarchaeologist should be able to bridge between different scales, and should be actively involved in the field during excavation. This would allow formulating relevant questions and appropriate lines of research. By this active participation, proper sampling strategies—with stratigraphy as the central point around which all specialists and specialisms revolve—could also arise.

SEE ALSO: Coring; Formation Processes; Soil Survey

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High Performance Liquid Chromatography (HPLC)

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Introduction

High performance liquid chromatography (HPLC) is a kind of column chromatography conducted under high operating pressures that is used to separate the compounds in a liquid mixture.

The concept of chromatography was born in the early twentieth century when a Russian botanist, Mikhail Tswett, separated a mixture of plant pigments in a column. He presented his work in 1903 at the meeting of the Warsaw Society of Natural Sciences, and the term “chromatography” was introduced three years later in his publication. HPLC was developed only in the 1970s–80s together with new instrumentation and columns filled with small particles. These solutions led to superior resolving power, an increase in specificity, precision, and accuracy, as well as a reduction in the sample amount and analysis time.

Nowadays, modern HPLC is supported by a wide range of detectors, which provide information about the complexity, identity, and quantity of the components in a mixture using the physicochemical properties of the analytes. Furthermore, the successful coupling of HPLC with mass spectrometry (MS) (see MASS SPECTROMETRY (MS)) offers the perfect analytical tool that combines the excellent separation capability of HPLC with the unsurpassed sensitivity and specificity of MS. All this makes HPLC one of the most important separation techniques that, unlike gas chromatography (GC), is not limited by analyte molecular mass, volatility, or thermal stability; thus HPLC can be used to separate solutes over a wide polarity range, from small organic molecules and ions to large biomolecules and polymers.

Concept

HPLC separation requires two phases: the stationary phase, which is the solid media packed into a column; and the mobile phase (eluent), which is a liquid forced through the column under high pressure. A bed of the stationary phase is formed by fine, totally porous or pellicular particles (a solid core with a thin porous outer shell) of 5 μm diameter or less with a narrow size distribution. Their surface can be modified by either physical or chemical means, which is the starting point for various chromatographic modes. The mobile phase is usually a mixture of two or more solvents, water, aqueous buffer solutions, and/or miscible organic solvents, which is capable of dissolving the analytes. Differential migration of sample components through the column depends on the equilibrium distribution of each compound between the mobile and stationary phases. The equilibrium distribution is continuously disturbed by flows of the fresh mobile phase, and re-established immediately by mass transfer from one phase to another. Consequently, the solutes move along the column, and the movement is determined by the composition of the mobile phase, the composition of the stationary phase, and the separation temperature.

Basic HPLC systems consist of a pump (with a mixing chamber), injector (manual or automatic), column (the heart of the chromatograph), and detector that are connected together via tubing with a narrow inner diameter (to minimize band broadening), as well as a data collection device that visualizes a detector signal in the form of a chromatogram.

The peaks of various sizes rising from a baseline of the chromatogram provide information about each component of the sample. The retention is a measure of the velocity at which a solute moves in a chromatographic system. The position of a peak in a chromatogram is characterized by its *retention time* (t_R), which is defined as the time elapsed between the injection and the appearance of the peak maximum (Figure 1). The retention time consists of two components: the

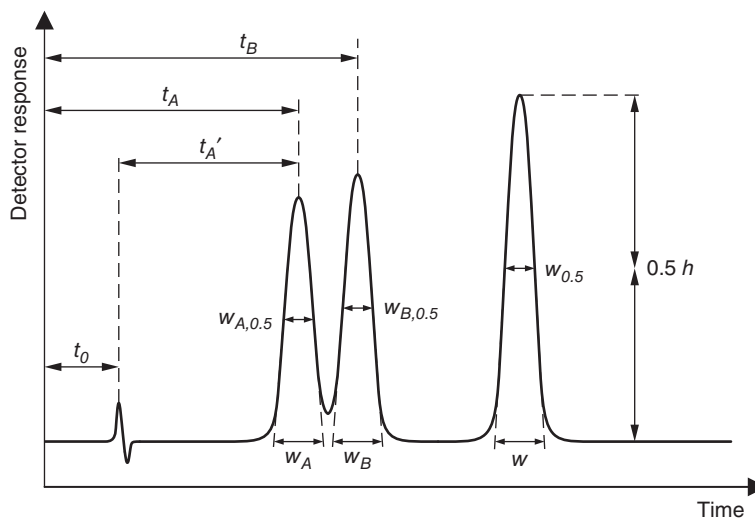


Figure 1 Chromatographic parameters.

time that the solute spends in the mobile phase, and the time it spends in the stationary phase. The first component corresponds to the time taken by an unretained compound, (i.e. a solute that does not interact with the stationary phase at all), which is called the *column hold-up time* (t_0), while the second component is the difference between retention and hold-up time, known as the *adjusted retention time* (t'_R).

The identification of analyte is based on the comparison of the retention parameters of an unknown with those of reference materials determined under identical experimental conditions. Although retention is a property of a solute, it is not a unique property. Therefore identification often requires comparison of other qualitative information based on physicochemical properties of an analyte, such as molecular mass, characteristic absorption or re-emission of electromagnetic radiation that can be provided by the detector. The linear relationship between detector response (peak area or height) and the concentration of the analyte is used to determine the amount of each analyte in the sample.

The column should have the capacity to retain the solutes, and it should be selective to resolve them. The chromatogram of well-separated compounds should present peaks located as close to each other as possible, but not overlapping. The degree of separation between two peaks is expressed as the *resolution* (R), which describes

the relationship between distance of the peaks and their average *widths* at the bases (w) obtained by extrapolating the relatively straight sides of the peaks to the baseline, or at their half height ($w_{0.5}$) (see Figure 1).

$$R = 2(t_B - t_A) / (w_A + w_B) \\ = 1.18(t_B - t_A) / (w_{A,0.5} + w_{B,0.5})$$

The goal of HPLC separation is to provide the optimal resolution at minimum time. If individual values of the resolution are 1 or greater, the separation is complete, but it does not mean that the baseline between the peaks is reached. The valley is of about 94 percent for two peaks of similar height. Entire separation is only obtained if the resolution is 1.5, and it needs to be higher in the case of a greater height ratio between the peaks.

The resolution can be improved by increasing the *selectivity* (α), *average capacity factor* (k'_{av}), and *number of theoretical plates* (N) that characterize the column efficiency. k'_{av} is dependent mainly on the packing material, but it can be varied by modifying the composition and strength of the mobile phase. Also α is a function of the porous media in a column, but it can be altered by changing some of the eluent parameters as well (the constituents, strength, temperature, and pH). Peak broadening, and hence efficiency, depends on the column itself (the dimensions, particle size, and quality of the column packing) as well as on the mobile phase flow rate.

Table 1 Characterization of HPLC modes.

<i>HPLC mode</i>	<i>Stationary phase</i>	<i>Mobile phase</i>	<i>Analytes</i>
Normal-phase liquid chromatography (NPLC)	Silica, alumina, polar bonded phases	Nonpolar solvent mixed with slightly more polar solvent	Polar solutes readily soluble in organic solvents
Hydrophilic interaction liquid chromatography (HILIC)	Silica, polar bonded phases	Aprotic solvent (miscible with water) with a small amount of water	Highly polar compounds or with limited solubility in water
Reversed-phase liquid chromatography (RPLC)	Hydrophobic bonded phases	Water or aqueous buffers (alternatively with ion-pairing reagent) mixed with polar organic solvent miscible with water	Solutes with wide range of polarity
Ion-exchange chromatography (IEC)	Anion and cation exchange resins	Aqueous solutions of salt, often mixed with small percentage of organic solvent	Mainly small inorganic and organic ions
Size-exclusion chromatography (SEC)	Highly porous substrate	Aqueous buffers or organic solvents capable of dissolving analytes	Biomacromolecules, polymers
Affinity chromatography	Matrix with bonded biochemicals (affinity ligands)	Aqueous buffers with appropriate pH and ionic strength	Proteins, nucleic acids

Strategies

HPLC elution of solutes from the column can be carried out with two operating methods. Isocratic elution consists of keeping a constant composition for the mobile phase during the analysis. It is suitable for the solutes of similar affinities for the stationary phase. However, many complex samples contain components that differ widely in retention. In that case the peak width of strongly retained solutes increases with increasing retention time, causing difficulties in their detection. The resolution can be improved using a gradient elution technique that assumes changes in the eluting strength of a mobile phase, and hence in its composition, during the chromatographic process. This is achieved by employing two to four different solvents or their solutions. As a consequence, it is possible to separate both weakly and strongly retained solutes while achieving appropriately short elution times for the later peaks.

The particular combinations of stationary and mobile phases are the bases for a wide variety of separation modes (Table 1), such as normal-phase, reversed-phase, hydrophilic interaction, ion-exchange, size-exclusion, and affinity chromatography.

Reversed-phase liquid chromatography (RPLC) is the most widespread separation mode in modern HPLC that uses a nonpolar stationary phase and a polar mobile phase. The most widely used stationary phase is silica modified with a C18 group, but phases with bonded C8, phenyl, pentafluorophenyl, or cyano groups are also applied. Typical mobile phases consist of water or aqueous buffers mixed with polar organic modifiers miscible with water, such as methanol, tetrahydrofuran, and acetonitrile. Differences in the selective interactions of these organic solvents (strong acidic hydrogen bonding of methanol, strong basic hydrogen bonding of tetrahydrofuran, and strong dipole interactions of acetonitrile) cause the differences in solubility of their mobile

phases. Moreover, the use of ionic additives (i.e., buffers, neutral salts, weak acids, ion-pairing reagents) allows exploitation of secondary chemical equilibria, such as ion suppression, ion-pair formation, or metal complexation, to change the selectivity of the separation process. Consequently reversed-phase liquid chromatography is applicable to simultaneous separation of a very wide range of nonpolar and polar solutes, including ionic, acidic, or basic analytes, homologous or oligomeric series with different numbers of nonpolar or weakly polar groups or moieties. The solutes are generally eluted in order of decreasing hydrophobicity, wherein if the gradient elution is used, the retention decreases with the increase of organic modifier content in the mobile phase equivalent to the decrease of the polarity of the mobile phase.

Conventional HPLC allows for a satisfactory analysis time, band broadening, and efficiency at pressures limited to 400 bar. However, the use of smaller core-shell particles (less than 2.5 μm) and thus shortening of the diffusion path can improve these parameters. Due to the exceptionally high working pressures up to 1200 bar and rapid mass transfer at high flow rates of the mobile phase, ultra-high performance liquid chromatography (UPLC or UHPLC) is capable of analyzing solutes with even greater speed, resolution, and sensitivity.

Detection

The detector constitutes an integral part of the HPLC system that monitors changes in some physicochemical properties of the column effluent and converts them into an electrical signal. There are various types of detectors, such as optical (see OPTICAL SPECTROSCOPIES), electrochemical, or spectrometric detectors, but the UV-Vis (spectrophotometric) detector is the most commonly used in RPLC because of its wide linear range, relative sensitivity, applicability to gradient elution, low cost, and ease of use.

Spectrophotometry belongs to the spectroscopic techniques based on the characteristic absorption of ultraviolet and/or visible radiation by compounds containing chromophores (parts of molecules, mostly multiple bonds, such as

$\text{C}=\text{C}$, $\text{C}=\text{O}$, or $\text{C}=\text{N}$, that can be excited). Since dienes absorb around 215 nm wavelength radiation and higher, aromatics around 254 nm, phenols roughly 260–280 nm, and the other chromophores causes further shifts to longer wavelengths (bathochromic effect), the UV-Vis detector is useful in detecting most organic compounds.

Two types of absorption detector are particularly popular: the variable-wavelength detector (VWD), which is capable of monitoring only a single detection wavelength at a time, and the diode-array detector (DAD), which is able to record chromatograms at multiple wavelengths simultaneously, whereas polychromatic light passing through the sample can provide also the full spectrum of each peak.

The next detector uses fluorescence emission, which makes it much more sensitive and compound-selective than a UV detector. However, it is much less commonly used, since most compounds do not have useful native-fluorescing properties. Consequently, derivatization of the analytes is obligatory to detect them.

The use of mass spectrometry (MS) (see MASS SPECTROMETRY (MS)) as a HPLC-detection technique has recently become more widespread. Such a hyphenation combines the advantages of both analytical techniques, providing a more powerful tool for identification and quantitation. The MS offers very low detection limits, excellent separation capability, and high selectivity that increases either with the MS resolution or with the use of fragmentation. Tandem mass spectrometry (MS/MS) either provides structural information about the analyte or allows better selectivity and sensitivity for quantitative analysis, based on analyte fragmentation. In consequence, HPLC-MS/MS in the multiple reaction monitoring mode (MRM) is extremely powerful for target-compound analysis.

Since the MS can only detect charged species, the critical point of this system is the interface that is able to generate ions directly from solution and transfer them into the gas phase. This is possible thanks to atmospheric-pressure ionization techniques, such as electrospray ionization (ESI), atmospheric-pressure chemical ionization (APCI), and atmospheric-pressure photo ionization (APPI). Their applicability depends on the polarity and size of the analytes, hence ESI

is the most common interface combined with RPLC. The basic compounds ionized by ESI are mostly protonated, and thus positively charged $[M + nH]^{n+}$, while the acidic compounds are deprotonated forming negative ions $[M - nH]^{n-}$ (in most cases $n = 1$). Ionization can be aided by the use of pH control buffers commonly used in RPLC, but only volatile ones (i.e., ammonium bicarbonate, ammonium formate, formic acid) that are also compatible with an ESI MS system.

HPLC in archaeology

Archaeological objects are unique research materials: not only extremely complex (they contain original components, degradation products, and various contaminants), but also valuable. Although HPLC requires sampling followed by extraction of the analytes, and in consequence by destruction of the examined pieces, it may deliver comprehensive information on the organic compounds isolated from the extremely small samples that cannot be obtained by any noninvasive or nondestructive technique. Thus research on archaeological objects can be classified as a typical trace analysis applied in forensic science.

Since natural dyes (see DYES) consist of a mixture of colorants, RPLC is the most widely used technique for their identification in textiles (see TEXTILES), paintings, varnishes, polychromies, and papers. Separation of the components is carried out mainly on a C18 stationary phase—universal and recommended for the analysis of natural products. The hydrophobicity of coloring compounds is very diverse and requires the use of a gradient elution, wherein the mobile phase is usually a mixture of water with methanol or acetonitrile with addition of pH modifiers (i.e., formic acid, trifluoroacetic acid, phosphoric acid, or phosphate buffer), but their choice depends to some extent on the detection technique. Other stationary phases, such as phenyl, C4, C8, and NH_2 , are much less frequently used, although some of them provide very good results. The amino column requires the use of an ion-pairing reagent, such as sodium dodecyl sulfate (SDS).

All colorants that are components of natural organic dyes can be effectively separated

by RPLC, even if some of them have very long retention, but not every kind of detection can be used to detect them all (Figure 2). Two detectors, UV-Vis and MS, are the most widely used in the identification of dyestuffs. In so far as the use of spectrophotometry is particularly reasonable for the study of colorants (due to the numerous chromophores, they strongly absorb radiation not only in the ultraviolet, but also in the visible range), mass spectrometry is not so universal in this case. Some nonpolar compounds, such as 6,6'-dibromoindigotin, crocetin, or bixin, are ionizable to a negligible extent, especially with ESI. However, since this group is not common, and the advantages of the ESI MS detector towards the other colorants are enormous, a coupling of both detection techniques is an increasingly common solution that provides a complete set of information about the sample.

HPLC-MS is applied to analyze triacylglycerols in archaeological residues (see FOOD RESIDUE ANALYSIS and ORGANIC RESIDUE ANALYSIS), and also lipid binders (see PIGMENTS AND BINDERS), as it provides more accurate results than typically-used GC-MS (see GAS CHROMATOGRAPHY-MASS SPECTROMETRY (GC-MS)). Separation is performed in the reverse phase mode using a C18 column with gradient elution (mainly methanol/isopropanol, or acetonitrile/dichloromethane). Detection can be carried out with both APCI MS and ESI MS, but it needs to be compatible with the eluent used. The achieved triacylglycerol profiles give the content of individual fatty acids, so providing the necessary information to determine the origin of fat in a sample.

Proteinaceous binders (see PIGMENTS AND BINDERS) in artistic paintings can be identified by HPLC with UV-VIS or fluorescence detection, but the analysis of hydrolyzed amino acids requires a pre-column derivatization. The best separation results on a C18 stationary phase are provided by phenylisothiocyanate, 4-dimethylaminoazobenzen-4'-sulphonyl chloride used with UV-Vis detection, as well as by 9-fluorenylmethyl chloroformate and 6-aminoquinolyl-*N*-hydroxysuccinimidyl carbamate combined with a fluorescence detector, whereas a solvent system is based on sodium acetate, triethylamine, water, and acetonitrile. However, there is also an alternative to the

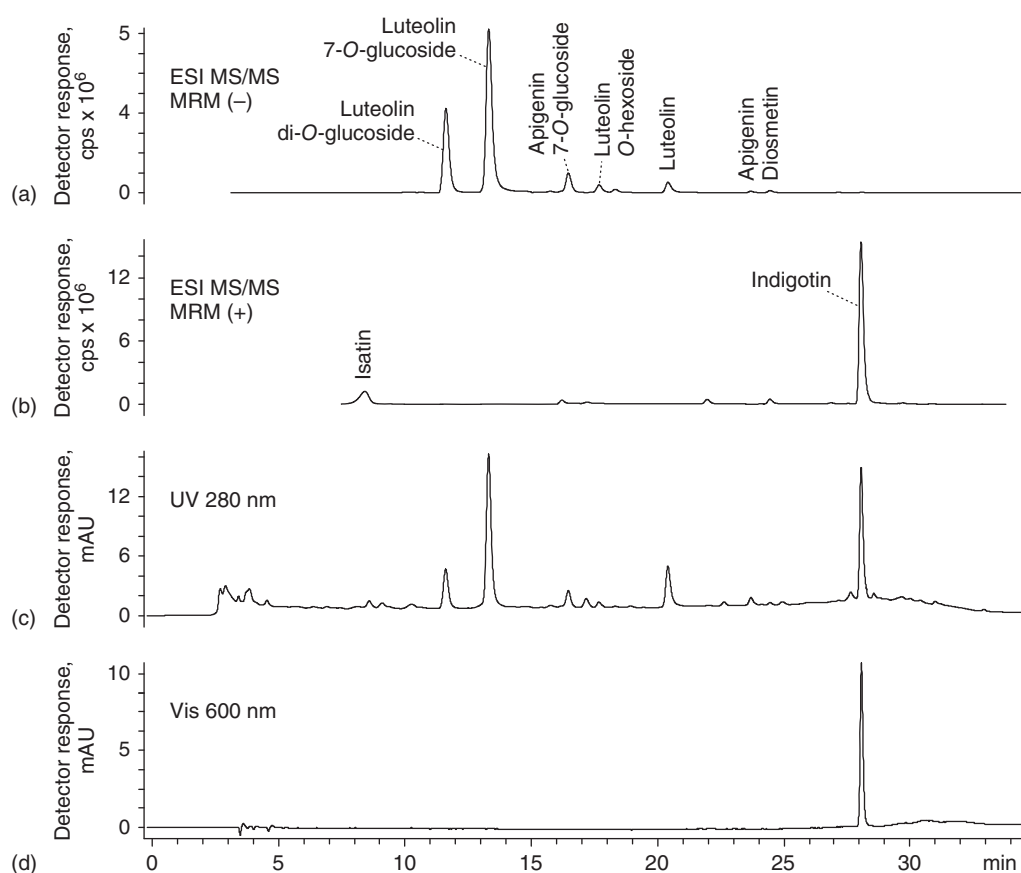


Figure 2 HPLC chromatograms of extract from green fiber (from a fifteenth-century chasuble dyed with weld and woad) provided by an ESI MS/MS detector in (a) the negative and (b) the positive ion mode, and by UV-Vis detector at (c) 280 nm and (d) 550 nm.

derivatization. The first approach is to apply ion-pairing reagents together with less popular but specific detectors, such as a chemiluminescent nitrogen detector. The second concerns the use of HILIC coupled with ESI MS/MS.

The identification of natural dyes, binders, or food residues is based mainly on a fingerprint approach that compares a complex set of peaks with those achieved for the reference samples. However, if the characteristic chromatographic profile or markers do not exist, the identification approach may involve multivariate analysis (see MULTIVARIATE ANALYSIS) methods, such as principal component analysis (see PRINCIPAL COMPONENT ANALYSIS) (PCA) and partial-least squares discriminant analysis (PLS-DA), where chromatographic data constitute the basis of further analysis and identification.

HPLC used for chromatographic purification and isolation of collagen peptides significantly improves ¹⁴C bone dating (see DATING IN ARCHAEOLOGY).

SEE ALSO: Chromatographic Techniques in Conservation; Chromatography and Archaeological Materials Analysis; Gas Chromatography–Mass Spectrometry (GC-MS); Mass Spectrometry (MS)

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Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR)

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Infrared (IR) absorption spectroscopy is the study of the interaction of infrared radiation with matter. When irradiated, functional groups (clusters of atoms or bonds within molecules, e.g. $[\text{CO}_3]^{2-}$) in solid, liquid, and gaseous materials vibrate or rotate in specific modes that depend on the nature of atoms, interatomic chemical bonds and dynamic group properties. Each vibration mode corresponds to the absorption of a particular frequency in the infrared region ($14,000\text{--}20\text{ cm}^{-1}$), which results in a spectrum characteristic of a specific functional group (Diem 2015). Therefore, IR absorption spectroscopy can be used to identify different compounds in organic and inorganic substances, including materials of archaeological importance (Artioli 2010).

Infrared radiation was discovered in 1800 by Sir William Herschel, but its application to materials science did not expand until the 1930s, when the first commercial IR spectrometers were developed for the synthetic rubber industry. These instruments included an infrared radiation source, a sample chamber, a monochromator based on an optical grating or prism, and a detection system (Derrick, Stulik, and Landry 1999). A major technological breakthrough was the replacement of the monochromator with a Michelson interferometer in the 1960s. This device produces an interferogram that is converted into an infrared spectrum using the Fourier transform, thus improving the resolution of measurements and reducing noise and detection limits. This method, called Fourier transform infrared spectroscopy (FTIR), quickly

became the standard in IR studies. By the 1970s, FTIR spectrometers were combined with a dedicated computer, which dramatically increased the rapidity of measurements (Derrick et al. 1999).

FTIR measurements are mostly performed in transmission mode by calculating the absorbed component of the incident beam as a function of frequency. The beam passes through a few tens of micrograms of powdered sample suspended in a potassium bromide (KBr) pellet or dispersed in an oil film in between potassium chloride (KCl) windows. Both mediums do not absorb IR radiation. The non-absorbed component of the incident beam is collected by a detector. The frequency absorptions of the functional groups in the sample are obtained against a background of air to subtract the contributions from water vapor and carbon dioxide (CO_2). Sample preparation and measurement typically take less than five minutes. The identification of the different phases that appear in the infrared spectrum is done by comparison with reference spectra of standard materials (e.g., Chukanov 2014; the online library of the Kimmel Center for Archaeological Science, <http://www.weizmann.ac.il/kimmel-arch/infrared-spectra-library>). As the intensity of the IR absorptions has a precision ranging between 10–20%, FTIR spectroscopy is a method preferentially used to determine the presence of different chemical phases above the detection limit. Semi-quantification can be achieved by preparing standard mixtures for calibration. If the sample is crystalline, X-ray diffraction is preferred for quantification.

Another important acquisition mode of IR spectra is based on the reflection of the incident beam. In diffuse reflectance Fourier transform spectroscopy (DRIFT), about 2 mg of powdered sample mixed with KBr is placed in a cup-holder and leveled off to obtain a flat surface, which is then irradiated with infrared light. The beam penetrates the surface by a few micrometers and is partially absorbed and reflected by the functional groups in the sample. The diffusely reflected component of the beam is finally directed to a detector. The background spectrum is collected on a pure KBr powder. In attenuated total

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reflectance (ATR), the incident IR beam passes through a crystal of high refractive index (e.g., diamond, silicon, germanium, or zinc selenide) that is in contact with the surface of a powdered sample. The beam reflects within the inner surface of the crystal and generates an evanescent wave that penetrates into the sample by a few micrometers. The reflected component is then collected by a detector. The background spectrum is generally collected on air. DRIFT and ATR devices usually consist of sample chambers that can be conveniently attached to a regular FTIR spectrometer by replacing the transmission chamber.

Transmission and reflectance measurements can be performed also on extremely small samples by combining a spectrometer with an optical microscope, where the nosepiece includes optical objectives and IR condensers. Reflectance measurements are generally carried out in total reflectance mode, where the beam does not penetrate the surface, or in ATR mode following the procedure described above. In total reflectance, the background spectrum is collected on a gold plate. The IR microscope setup is particularly useful in the characterization of minute particles (approximately 50–300 μm), and thus it is suitable for the structural analysis of valuable works of art, as well as in forensic investigation (Derrick et al. 1999). FTIR microscopy can also be used in the analysis of archaeological sediments in thin-section (e.g., Berna et al. 2012). Therefore, it is possible to integrate chemical, mineralogical and spatial information regarding the different components that occur in sediments. The use of automated stages allows chemical mapping of relatively large areas.

Due to the small sample size required for analysis, FTIR spectroscopy has been applied to archaeological materials since the 1950s, and significantly contributed to the development of the fields of archaeometry and conservation science. More specifically, FTIR spectrometry has proved useful in the characterization of materials such as amber, parchment, textile, bone, mollusk shell, plaster and mortar, faience, varnishes, dyes, pigments, and organic compounds used in paintings (Derrick et al. 1999; Artioli 2010). For instance, DRIFT analysis has been successfully employed in the provenancing of amber artifacts by matching their infrared spectra with the spectra of geological samples from a reference database (Angelini

and Bellintani 2005). In addition, FTIR spectrometry is routinely used as a screening method to check the purity of charcoal, collagen, and cellulose for radiocarbon dating (Weiner 2010).

With the advent of portable spectrometers in the 1980s, FTIR spectroscopy became a rapid and convenient method for on-site analysis at archaeological excavations (Weiner and Goldberg 1990). This approach to fieldwork presents major advantages, including the possibility of obtaining real-time information regarding the archaeological record that can be used to modify the excavation strategy as needed, and the ability to trace the boundaries of features that are invisible to the naked eye. In addition, samples are collected only from specific archaeological contexts relevant to the research questions at stake and immediately analyzed, instead of blind-sampling the entire site for post-excavation laboratory work (Weiner 2010).

Since FTIR spectroscopy is sensitive to the molecular bond interaction level, this method is especially suited for the identification of both crystalline and amorphous/disordered inorganic materials, as well as organic materials. Disordered and organic materials are particularly common in sediments at archaeological sites, and include opaline phytoliths, bone collagen, charcoal, lignin, cellulose, and humic acids. Using FTIR spectroscopy it is also possible to assess the degree of atomic order of crystalline phases exposed to fire, which changes their interatomic chemical bonds, and thus identify pyrogenic calcite, heat-altered clay minerals, and burnt bone (Berna et al. 2007; Regev et al. 2010; Weiner 2010). Another important aspect is the state of preservation of the archaeological record, which depends on the nature of the sedimentary matrix and on environmental conditions at a specific site. Diagenesis may alter the chemical properties of sediments and artifacts and thus lead to misleading interpretations of formation processes and human occupation. FTIR spectroscopy can track the formation of authigenic diagenetic minerals such as phosphates, nitrates, and sulfates, which form under specific environmental settings (Karkanas et al. 2000). In general, the results of FTIR analysis are best interpreted when integrated with the information obtained through other methods that address

the microscopic record, such as micromorphology (see MICROMORPHOLOGY) of sediments, phytolith analysis (see PHYTOLITH ANALYSIS), X-ray fluorescence (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), X-ray diffraction, Raman spectroscopy (see RAMAN SPECTROSCOPY), and more. This approach allows a better understanding of the archaeological record as a whole (see also MICROARCHAEOLOGY).

FTIR spectrometry is therefore a valuable method for the chemical characterization of archaeological artifacts and sediments, and can significantly contribute to addressing problems related to the preservation of the archaeological record, site formation processes, post-depositional alterations, stratigraphic correlations, absolute chronology, pyrotechnology, and more in general to past human activities. Currently, FTIR spectroscopy is being used to explore in more detail the different degrees of atomic disorder of mineral species altered or produced by fire and diagenesis, such as calcite (plaster and mortars), aragonite (wood ash), quartz (stone tools), clay minerals (combustion features), carbonate hydroxylapatite (bone and enamel), and other phosphates (authigenic). This requires the characterization of small samples within their original depositional context or structural configuration, and thus FTIR microscopy on thin-sections is a preferred method of analysis (Berna 2017). However, the large amount of point data collected from a thin-section poses the question of imaging and mapping of extensive surfaces into sizeable output, and the need for dedicated statistical means of interpretation of large datasets of infrared spectra. It can be predicted that in the near future the mapping of relatively large surfaces will be routinely applied to works of art that cannot be altered with sampling, such as paintings and frescoes, by using portable reflectance devices that operate in the near- and mid-IR spectral range (14,000–400 cm⁻¹). This approach will be extended also to standing sections of sediment at archaeological sites.

SEE ALSO: Archaeological Fieldwork; Archaeometry; Archaeomineralogy; Chemistry in Archaeology; Diagenesis of Bone; Formation Processes; Geoarchaeology; Human Skeletal Geochemistry; Infrared Reflectance Spectroscopy; Microarchaeology;

Micromorphology; Mortuary Analysis; Raman Spectroscopy; Raman Spectroscopy and Material Analysis; Raman Spectroscopy in Conservation; Soil Chemistry in Archaeology; Taphonomy

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Ion Beam Analysis (PIXE/RBS)

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Ion beam analysis (IBA) methods can provide information on chemical composition and elemental distribution in a material. The strengths of IBA relative to other compositional techniques are the operation in air in a non-invasive way, analyzing objects of any shape and dimension, obtaining spatially resolved information (both surface mapping and depth profiling), with multi-elemental and quantitative analysis at very low concentrations (parts per million). Drawbacks of IBA are the non-portability, the impossibility of analyzing samples that are radiation or heat-sensitive, and the fact that the probing depth is limited to the superficial layers (maximum 200 microns). Moreover, since a small particle accelerator is required to generate the probing beam, the availability of IBA is limited to a small number of laboratories.

IBA is employed in the archaeological field to answer questions and solve problems that cannot be addressed using other analytical techniques, allowing the identification of materials, provenance studies, and evaluation of fabrication techniques and state of conservation. Its importance has increased over time thanks to the continuous technological improvements that have extended the number, shape, dimensions, and complexity of samples that can be analyzed.

IBA techniques require a particle beam (usually protons or alpha particles) with energies of a few mega-electronvolts impinging on the sample to be analyzed. Even though the first design of accelerator used for IBA dates back to the 1930s, complete applicability of the technique to the field of archaeology was reached only in the 1970s, when the first beam operating in air (and not in

a vacuum, as previously) was developed. In the 1980s another advancement was the adoption of focused ion beams down to a micron level, which increased the spatial resolution capabilities of IBA techniques and enabled mapping of the distribution of elements. IBA techniques are still continuously improving their performance and analytical capabilities; a review of recent achievements and future challenges can be found in Zucchiatti and Redondo-Cubero (2014).

The interaction of the beam particles with the nuclei and electrons inside the sample gives rise to many signals that can be detected, giving different information useful for different IBA techniques; a full list of these techniques can be found in Jeynes et al. (2012). In the archaeological field the best-used IBA technique is PIXE (particle induced X-ray emission), where the X-rays characteristic of the atoms inside the sample are detected, allowing the identification of the elemental composition (usually for elements heavier than sodium). The physical principle of X-ray emission is the same as that exploited in SEM-EDS and XRF (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), although those use different probes (electrons and photons respectively). The advantage of PIXE with respect to EDS is the greater sensitivity, allowing simultaneous detection of main, minor and trace elements (thanks to the lower braking radiation (“bremsstrahlung”), the detection limits are usually around 1–10 ppm) and the possibility of analyzing samples of almost any shape, dimension and material, not requiring a vacuum and so without the space limitations of a chamber. Even if other techniques (e.g., ICP-MS (see ICP-MS AND MATERIAL ANALYSIS)) can detect elements present at lower concentrations, PIXE and XRF are the only ones that can work in a non-invasive mode. While XRF can be portable (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)), an aspect very appealing in the archaeological field, PIXE requires the samples to travel to the laboratory to be analyzed. But once there, PIXE can quantify the element contents (also ppm) by means of the acquisition of only one spectrum, while XRF needs different

runs of measurements acquired with different experimental conditions, to take into account phenomena such as diffraction. Another key advantage of PIXE is that it is often coupled with other IBA techniques, giving complementary information and providing a wider overview to answer archaeological questions.

By the end of the 1990s a portable PIXE instrument has been realized for applications in the field of heritage studies: it is based on an annular radioactive source that generates the probing alpha-particle beam. Despite the portability, which is a very important aspect for the analysis of archaeological materials, there are some limitations that have to be highlighted: it is not possible to obtain spatial information (nor the elemental distribution on the surface nor the depth profiling) or to combine it with other techniques. Moreover, there are some issues both in the production and the duration of the radioactive source and the radioprotection rules to be followed when moving this instrument outside the laboratory.

Another widely used IBA technique is RBS (Rutherford backscattering spectroscopy), similar to the SEM-BSE, but using an ion probe instead of an electron probe. It is based on the measurement of the number and energy of the beam particles backscattered by the sample at a high angle (typically from 150–170° with respect to the beam direction). It gives information on the composition of the material (elements heavier than the impinging particles, which are usually H or He) with a sensitivity that, for heavy atoms, reaches the ppm level. Moreover it is possible to obtain information on the depth profile distribution of different elements, in the most favorable cases with a resolution of a few tens of nanometers. It is best suited for the analysis of elements with medium and high weight in a light matrix and can give information up to around 10 µm depth. Due to absorption phenomena, RBS has some limitations when used in air or helium flux.

Other IBA techniques have been used in the archaeological field, usually coupled with one of the two main ones (PIXE and RBS) to give complementary information. Among them are:

- PIGE (particle induced gamma-ray emission), based on the detection of gamma-rays

emitted by a nucleus interacting with a particle and able to detect light elements (usually from lithium to sodium);

- IBIL (ion beam induced luminescence) or IL (ionoluminescence), similar to the cathodoluminescence used in electron microscopy, where the detection of UV-VIS-NIR photons emitted by the sample allows the identification of different phases, chemical zoning in minerals, or the presence of elements in very low concentrations (ppm) that are involved in luminescence centers (radiative recombination);
- NRA (nuclear reaction analysis), in which the products of nuclear reactions (usually protons or alpha particles) are detected, allowing the depth-profiling of some elements and the possibility of distinguishing among some isotopes;
- ERDA (elastic recoil detection analysis), where light atoms knocked out from the samples by heavy ions are detected (usually $Z < 15$, including hydrogen).

PIGE and IL can be used in air or helium flux, whereas NRA and ERDA give better results if employed in a vacuum on small samples, due to absorption effects.

In recent decades, a number of laboratories have developed one or more of the IBA methods and used them to analyze materials of interest in the archaeological field. A special mention is due to the AGLAE laboratory, which has operated in this sector at the Louvre Museum in Paris for almost 30 years; it is among the few IBA laboratories mainly devoted to the analysis of materials related to archaeology and heritage (Dran et al. 2004).

IBA techniques have been used to answer different archaeological questions and to analyze many different materials. The easiest questions IBA can answer is the identification of an unknown material through its chemical composition (metals, alloys, stones, gems (see GEMSTONES), glass (see GLASS AND FAIENCE), pottery (see ELEMENTAL ANALYSIS OF POTTERY), pigments (see CHARACTERIZATION OF PIGMENTS), bones (see BONES AND IVORY), etc.).

A more challenging question that IBA can often answer is the provenance of a material based on extensive compositional databases of

reference compounds. This topic is of particular interest for reconstructing old trade routes and exchanges, for which no written testimonies remain. Provenance studies usually require wide and long experiments, and the availability of many samples from known provenances that are employed to create a database. Some elemental markers have to be found, characterizing each provenance; usually trace elements or luminescence properties are very useful for this purpose, and binary graphs of two elements or multivariate analysis can help to group the results and highlight the differences among the provenances. After that, the unknown sample is measured and compared with the database to find which group of known sample it most resembles. This approach, often combining data from PIXE, PIGE, and IBIL, has already been used on different kinds of materials like glass (see GLASS AND FAIENCE), natural glasses (obsidians (see CHERT, SILEX, AND OBSIDIAN SOURCING)), stones (flint, lapis lazuli, jade, volcanic materials), gems (see GEMSTONES) (rubies, emeralds, garnets), pottery (see ELEMENTAL ANALYSIS OF POTTERY) (ceramics, porcelain), metals (gold, copper, iron), alloys (bronze), pigments (see CHARACTERIZATION OF PIGMENTS) and ivory (see BONES AND IVORY).

Using a similar approach, indirect dating (see DATING IN ARCHAEOLOGY) of an artifact can be obtained. If many samples produced in a known period are analyzed and create separated clusters on the basis of the concentrations of some chemical element (mainly trace elements), then, analyzing an unknown sample, it is possible to correlate it to the group of corresponding composition, and so to obtain an indirect dating for the sample. This method has already successfully been used for glasses (see GLASS AND FAIENCE) and pottery (see ELEMENTAL ANALYSIS OF POTTERY).

IBA also offers a unique tool to study other characteristics of archaeological materials, related to their fabrication techniques. For example, thanks to the combination of RBS and PIXE, a gilded object can easily be discriminated from a golden one, and the gilding thickness and composition can be evaluated. Another aspect related to metals is soldering (Demortier 1991); different techniques used by craftsmen can be distinguished, providing information about the technological level that a population reached in

different periods, and also about the presence of restorations (also made in antiquity).

The analysis of coins can provide useful information too: a debasement in the amount of noble metals can be correlated to periods of war or crisis, while the detection of trace elements can correlate different populations, suggesting exchanges among them. The study of differences between surface and bulk can also expose fakes or counterfeit coins, presenting a surface rich in the noble metal and a core where it is present in very low concentrations or absent (Beck et al. 2011).

Another aspect that IBA can help to clarify is related to the state of conservation (see CONSERVATION) of an archaeological object, and in particular about the presence and thickness of an alteration patina due to its burial or conservation conditions. In this case, the combination of RBS, PIXE and NRA, or the use of ERDA, can give the thickness and depth distribution of multiple alteration layers on metals, alloys, and glasses (see GLASS AND FAIENCE).

SEE ALSO: Archaeometry; Bones and Ivory; Characterization of Pigments; Chert, Silex, and Obsidian Sourcing; Conservation; Dating in Archaeology; Elemental Analysis of Pottery; Gemstones; Glass and Faience; ICP-MS and Material Analysis; Portable X-Ray Fluorescence Spectrometry (pXRF); X-Ray Fluorescence Spectrometry (XRF)

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FURTHER READINGS

Isotopes

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Introduction—elements, atoms, and isotopes

All naturally occurring materials are built of *elements*. Already in 1911 Ernest Rutherford had postulated that the large-angle scattering of positively charged α -particles that he observed could be produced only by an intense electric field, due to a positive charge, with most of the mass of the atom concentrated in the center, later named the *nucleus*. It was subsequently shown that elements consist of atoms built of a nucleus with a specific number of positively charged *protons*, and electrically neutral particles of similar weight known as *neutrons*. In its atomic shells the nucleus is surrounded by orbiting, negatively charged particles called *electrons* (Figure 1). The mass of electrons, by comparison with the protons and neutrons, is so small that it does not contribute significantly to the total mass of an atom. The positively charged protons and negatively charged electrons compensate the electrical charge of the atom; if the number of electrons is smaller or larger than the protons, the atom is electrically charged and then it is called an *ion*.

The number of protons in the nucleus is characteristic for each element and known as the *atomic number* (Z); this number is also equal to the number of electrons in the atom, which defines the chemistry of the atoms. The total mass of protons and neutrons defines the atomic mass of an element, called the *mass number* (A). In 1914 an English physicist, Joseph John Thomson, observed that the gas neon is composed of two types of atoms of atomic weights about 20 and 22. Several other scientists confirmed in the following years the hypothesis that the place occupied in the Periodic Table by a particular element must accommodate more than one kind of atom (Faure

1986, 4–5). These different atoms of the same element, having different masses, therefore different *mass numbers*, English chemist Frederick Soddy named for the first time in the years 1912–20 the *isotopes*, from the Greek for “same place” in the Periodic Table.

Each element is characterized by its *atomic number*, equal to the number of protons in its nucleus, while its isotopes are described by the *mass number*, which is equal to the sum of protons and neutrons in the nucleus of their atoms. The usual way of describing the atoms is writing the mass number on the upper left and sometimes the atomic number below, for example, the most abundant isotope of carbon is in the form $^{12}_6\text{C}$, where the number in the superscript, the atomic mass, is specific for the isotope of a given element. Since the symbol identifies the element specifically, the atomic number is most often omitted in the literature, as in the well-known isotope of carbon, ^{14}C .

The word *isotope* is sometimes used in parallel with the word *nuclide*, defined as a specific atom characterized by the components of its nucleus, in particular by the number of protons and neutrons in its nucleus.

Naturally occurring isotopes

Radioactive isotopes

Isotopes can be *stable* or *radioactive*, spontaneously mutating to another isotope with the emission of particles or gamma rays. The radioactive decay of a parent nuclide into a radiogenic daughter isotope (which may also be radioactive and decay further) is a process progressing at a constant rate specific for a given nuclide, called the half-life ($t_{1/2}$). The half-life is the time required for half of the given initial number of radionuclides to decay, according to the equation:

$$\frac{1}{2}N_0 = N_0 e^{-\lambda t_{1/2}}$$

where N_0 is the original number of nuclides, and λ is a physical constant.

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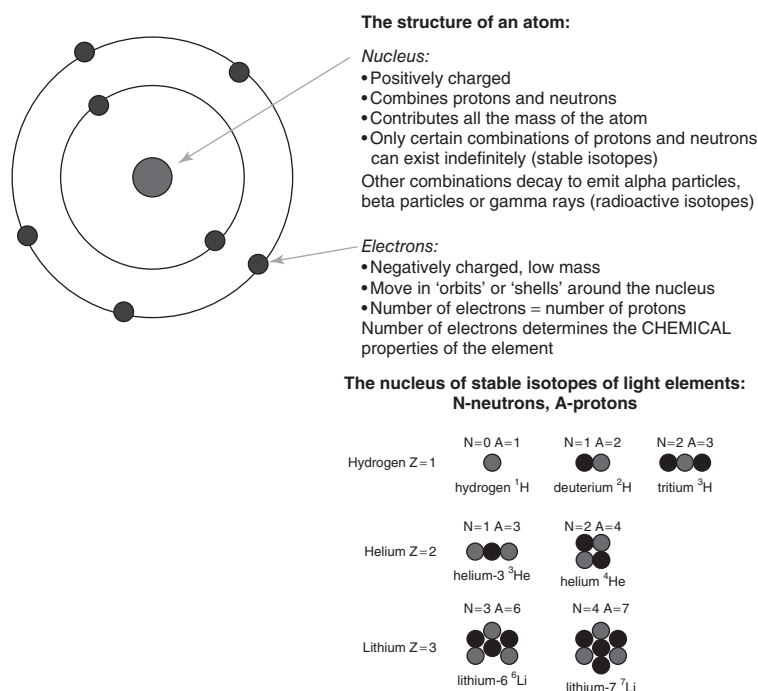


Figure 1 Schematic representation of an atom, and nuclei of some light isotopes.

This process depends only on the nuclear structure of the nuclide and is independent of chemical and physical conditions such as temperature, pressure, humidity, and elemental compositions. The half-lives of various nuclides vary from microseconds to many millions of years. For example, ^{238}U has a half-life of 4.5×10^9 years, ^{14}C a half-life of 5.73×10^3 years, but ^{210}Pb only 22.6 years. In cases when a material contains radioactive nuclides, the measurement of their concentrations can be used for their dating.

Some radioactive isotopes can be used for identification of the elements and their quantity by measurement of the type and energy of their radiation (α , β particles, γ radiation), as for example in ^{14}C and U/Th dating as an alternative to mass spectrometry.

Other radioactive isotopes can be created artificially in nuclear reactors, for example, strontium, arsenic, copper, silver and gold have short-lived isotopes that are commonly used in neutron activation analysis (NAA) of chemical compositions of archaeological pottery, metals, and obsidian.

Stable isotopes

In the natural environment, there are three main sources of isotopes:

- *Primordial*: formed during elemental synthesis in supernova explosions.
- *Radiogenic*: the results of the radiogenic decay of other elements.
- *Cosmogenic*: produced by the interaction of cosmic rays within the atmosphere and Earth's surface.

The overwhelming majority of naturally occurring isotopes are *primordial*, formed in supernovae, and were well mixed before becoming the Earth's crust. This mixing resulted in uniform isotopic compositions for most of the elements found on Earth. However, some *radioactive elements* disintegrate spontaneously and become the nuclides of another element, creating as the result of their decay *radiogenic* isotopes of other stable elements at the end of their *decay chain*. For example, the element lead

has four naturally occurring stable isotopes, of which one, ^{204}Pb , is primordial, while the other three, ^{206}Pb , ^{207}Pb , and ^{208}Pb , are radiogenic endpoints of the decay chains of ^{238}U , ^{235}U , and ^{232}Th , respectively. The abundance of stable radiogenic isotopes increases with time, therefore a considerable number of naturally occurring elements have variable isotopic compositions in the Earth's crust.

The production of isotopes due to cosmic radiation is of importance for the lighter elements in the atmosphere like helium ($Z=3$) and carbon ($Z=6$), and in the rocks, for example, for calcium ($Z=20$). For the light elements, in particular, fractionation due to slight differences in their chemical behavior can modify the isotopic abundances of natural elements, for example in photosynthesis, which enriches ^{12}C over heavier ^{13}C .

Early investigations demonstrated that the elements with atomic numbers between 1 (hydrogen) and 83 (bismuth) have on average more than three stable isotopes, each in varying proportions. Bismuth is the heaviest element that is not radioactive. The nine naturally occurring elements with Z greater than 83 are naturally radioactive; they include polonium, thorium, radon, and uranium. Current research continues to provide accurate measurements of the isotopic compositions of the naturally occurring elements to give isotopic reference materials and the basis for determination of the standard atomic weights of the elements. A recently published report of the Commission on Isotopic Abundances and Atomic Weights (Berglund and Wieser 2011) provides a list of isotopic compositions of all 81 elements with stable isotopes from hydrogen to lead (excluding technetium, Tc) with the best measurements of their abundances on Earth. The number of stable isotopes for each of the elements depends on their atomic mass, but does not vary in a regular manner. For example, calcium ($Z=20$) has six stable isotopes, where the atoms of ^{40}Ca constitute 96.9 percent of this element, while copper ($Z=29$) has only two stable isotopes, ^{63}Cu and ^{65}Cu , of abundance 69.2 percent and 30.8 percent respectively.

The measurement of abundances of stable isotopes

The first instrumental observations of differences in isotopic abundances of elements were made by J. J. Thomson in 1914. Francis William Aston improved the design of this instrument using a magnetic sector instrument, and called it a "mass spectrograph". During his life Aston developed increasingly precise mass spectrographs with which he discovered 212 of 287 naturally occurring isotopes, also calculating for the first time more accurate atomic weights of elements. Aston was awarded the Nobel Prize in chemistry in 1922.

In the following decades, many scientists worked on improvements to this instrument. In 1940 Alfred O. Nier published a new design for mass spectrometers based on a 60° wedge electromagnet, and after World War II his workshop built a dozen such mass spectrometers for other scientists to use in isotope research. This development contributed enormously to the development of geoscience.

All current isotopic mass spectrometers consist of three basic components: the ion source, which forms a beam of charged ions from the analyte; an electrostatic or electromagnetic deflector to separate ions of different masses (most commonly a magnetic sector); and a collector of ions to measure the ion current. Isotopes of very low abundance can be measured using *accelerator mass spectrometry* (AMS), or mass spectrometers with a *gas source* (for example, for hydrogen or oxygen).

The isotopes of heavy elements (for example, strontium, copper, tin, lead, silver, uranium, thorium) can be accurately measured by two different types of instruments: thermal ionization mass spectrometers (TIMS) and multicollector inductively coupled plasma mass spectrometers (MC ICP-MS) (Niederschlag et al. 2003, 61–64). The major difference between these two types of instruments is in the type of source of ionization of atoms. TIMS relies on a solid source, while in MC ICP-MS the ions are produced in an inductively coupled plasma source. For reasons of accuracy, and for reasons related to the geochronological applications, the isotopes are measured not as abundances, but as ratios of two or more isotopes.

Many research laboratories are equipped with a cheaper instrument with an ICP source built for analyses of trace elemental compositions of materials, but capable of isotopic measurements, called a quadrupole inductively coupled plasma mass spectrometer (ICP-Q-MS); this instrument cannot produce data accurate enough for provenance research of archaeological materials (University of Texas at Austin 2017). The same is true for another technique that in principle can measure isotopic compositions: the time of flight mass spectrometers.

Sample materials for mass spectrometric isotope analysis need to be dissolved, therefore it is necessary to take samples of ancient artifacts and materials. When MC ICP-MS is used, there is also a possibility of using *laser ablation* for introduction of the atoms of the material into the source. This method can be used for particularly precious materials, for example gold.

Stable isotope fractionation

Isotopes of some elements do not show identical chemical behavior during mineral-forming processes; for example, copper and tin minerals show varied isotopic compositions due to the process called isotopic fractionation during crystal formation. These isotopic variations can, under certain circumstances, be used in archaeometallurgical research.

SEE ALSO: Climate Change and Dating; Dating in Archaeology; Diet and Nitrogen Isotopes; Diet and Sulfur Isotopes; INAA and Material Analysis; Mass Spectrometry (MS); Mobility and Lead Isotopes

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Laser-Induced Breakdown Spectroscopy (LIBS)

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Principles of laser-induced breakdown spectroscopy

Laser-induced breakdown (or plasma) spectroscopy (LIBS or LIPS) is a versatile analytical technique allowing the identification and quantification of atomic species composing a material through the spectral analysis of the plasma generated by its irradiation with a high-peak-intensity (above $\sim 10^8$ W/cm²) laser pulse.

A pulsed laser beam with pulse energy and duration of ~ 0.1 – 100 mJ and ~ 0.1 – 10 ns, respectively, is typically used in LIBS systems as an excitation source. Its focalization on a solid surface in a liquid or gas with a suitable lens produces ionization and then a rapidly expanding plasma plume, which appears to the naked eye as a bright spark. This optical emission represents the visible result of a complex superposition of photons, electrons, atoms, and ions interaction dynamics, which has been the subject of thorough investigations since invention of the laser in 1960 (Raizer 1977).

Let us consider the case of a solid material irradiated using the above-mentioned nanosecond laser pulses at typical peak intensities of $\sim 10^9$ – 10^{11} W/cm², which can be easily achieved by focusing the laser beam with a lens. This induces local vaporization, atomization, multiphoton ionization, and acceleration of free electrons by sequential absorption of photons through the so-called inverse Bremsstrahlung process.

When the kinetic energy of the electrons overcomes the ionization energies of the atoms under irradiation, new free electrons are created by impact ionization. Above a critical electron density (around 10^{13} el/cm³), under

sufficiently high photon flux, an avalanche electron multiplication is induced, which is referred to as optical breakdown. A rapidly expanding dense plasma region (10^{18} – 10^{21} el/cm³) is thus formed with typical associated temperatures and speeds of $\sim 10^4$ K and $\sim 10^4$ m/s, respectively. The plasma onset is followed by a pumping phase depending on the laser pulse duration and intensity. This develops according to a fluid dynamic interaction regime where the main ionization contribution is determined by collisions that extend the plasma lifetime well beyond the laser irradiation. The plasma parameters reach their maxima around the end of the laser pulse energy release; then quenching phenomena such as radiation emission, recombination, and other decay processes occur.

Laser-produced plasma emits optical radiation throughout its lifetime. During the onset phase this emission is dominated by the continuum spectrum of the electron Bremsstrahlung, which is not useful for material analysis purposes. Such a spectral contribution drastically decreases with the electron density after several hundred nanoseconds; then atom and ion electron transitions become predominant and their spectroscopic characterization becomes useful for elemental analysis (Cremers and Radziemski 2013). To this end, elimination of the former component represents a fundamental requirement that can be achieved by delaying the spectral acquisition with respect to laser irradiation. Spectroscopy within the present technique is hence carried out during the quenching phase of the laser-produced plasma, well after optical breakdown. This is the reason why some authors prefer to define the present technique as LIPS rather than LIBS, although the latter acronym is much more frequently used than the former.

From a technological standpoint, basically, a LIBS system includes the excitation laser source, focusing and collection optics, a pulse and delay generator, spectrometer (monochromator and sensor), and personal computer. In the schematic setup shown in Figure 1, the former is a Q-switched Nd:YAG laser, which is the

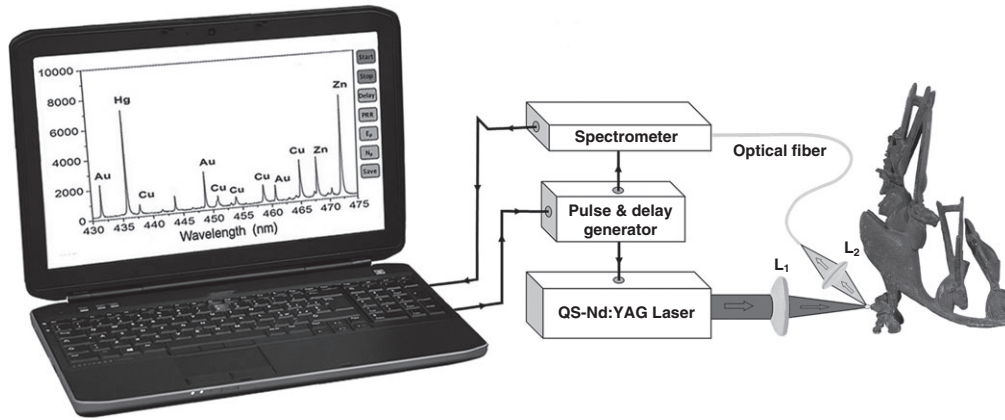


Figure 1 Schematic setup of LIBS.

most commonly used source, focused with the plano-convex lens L_1 . The plasma emission is collected by means of the lens L_2 (better if achromatic and aspheric) and coupled to the spectrometer through the optical fiber. The delay between the laser pulse and beginning of spectral detection (Δt) must be suitably selected in order to avoid the detection of the initial continuum emission. On the other hand, such a delay time should not be too long in order to avoid excessive cooling of the plasma and strong reduction of its luminescence, which would drastically reduce the signal to noise ratio (S/N). Often, time delays $\Delta t \approx 0.5\text{--}2\text{ }\mu\text{s}$ or, alternatively, corresponding shifts of the focal point of the collecting lens (L_2) are used.

The collection of the spectrum can be limited to a specific time interval (time gating) within the plasma lifetime or it can be longer than the latter. The former condition is useful when the hypothesis of local thermal equilibrium (LTE) is needed to measure the plasma parameters or to detect spectral lines with a relatively short lifetime. However, often short time gating is not a strict requirement and the typical free scan times of modern sensor arrays ($\sim 1\text{--}10\text{ ms}$) can be used. In this case, the accumulation time of the spectrum is determined by the plasma lifetime itself and its time of flight within the field of view of the collector, which typically varies between ~ 1 and $\sim 10\text{ }\mu\text{s}$.

A number of studies have reported on the dependence of the ablation and plasma dynamics involved in LIBS on laser wavelength and intensity aimed at optimizing the analytical

performance (see for example Fornarini et al. 2006). These pointed out that higher ablation rates and lower plasma temperatures are associated with ultraviolet–visible (UV–Vis) with respect to near infrared region–mid-infrared region (NIR–MIR) wavelengths, which is due to the inverse cubic dependence on the wavelength of optical penetration through the plasma region. Since higher plasma density, luminescence, and lifetime are usually preferable, NIR excitation sources such as a Q-switched Nd:YAG (1,064 nm) laser, including its more recent diode pumped version, are often used, although the experimentation has also included harmonics (532, 355, 266 nm), CO_2 (10.6 μm), and excimer (193, 248, 308 nm) lasers. Furthermore, since the beginning of this century, there has been a growing interest in ablative applications of femtosecond and picosecond excitation lasers, since they potentially provide better spatial resolution and absence of fractionation, although their advantages are still disputed.

As shown in Figure 1, individual lenses and optical fiber can be used for focusing the laser and coupling the plasma emission to the spectrometer. In this condition, the typical operative spot sizes range between about 10 and 200 μm . Moreover, LIBS is adaptable in microscopy setups using, for example, epi-axial coupling of the laser through the objective of the microscope, which replaces the lens L_1 , with consequent improvement of the lateral resolution up to the micrometric scale. Similarly, other optical components can replace the coupling lens L_2 .

Thus, in particular, a reflective collector using off-axis parabolic mirrors can be used to avoid problems related with the aberrations of a single spherical lens, and increase the repeatability of the measurements and reliability of portable devices thanks to its very stable setup (Agresti, Mencaglia, and Siano 2009).

The spectral resolution required for reliable LIBS analyses is relatively high (~ 0.1 nm) since atomic spectra of the materials are rather complex. In portable devices, this can conveniently be achieved using a set of ultra-compact spectrometers to cover the spectral range of interest. Such a class of low-cost instruments includes a Czerny–Turner monochromator and triggerable charge-coupled device/complementary metal oxide semiconductor (CCD/CMOS) sensor array, allowing delay of the acquisition with respect to its “trigger in” of Δt_1 . In some circumstances, if a given delay Δt_1 is set, a further intrinsic delay $\Delta t_0 \cong 0.3\text{--}1.5$ μs will be added by the sensor, which corresponds to the time needed for its reset. Thus, in those cases where delays $\Delta t \geq \Delta t_0$ provide a satisfactory optical signal, the spectrum detection can be triggered by the laser pulse itself (Figure 2a). Conversely, for relatively short lifetime plasmas and large Δt_0 , $\Delta t \leq \Delta t_0$ could be useful or needed in order to collect more signal. A simple solution is displayed in the example of Figure 2b, where an electro-optically Q-switched Nd:YAG excitation laser is considered: (1) the master trigger is generated and used to drive both the laser pumping and the spectrometer; (2) after a sufficient time, the QS triggering activates the laser and then the plasma emission; and (3) detection of the spectrum can be suitably delayed using the settable delay Δt_1 . In Figure 3, a detail of the spectrum of a ternary bronze sample is shown, which was detected about 600 ns after the laser pulse.

In laboratory setups, more sophisticated spectrometers have been often used, equipped with an echelle monochromator able to disperse the light in a wide range of spectral orders, associated with a time-gated and intensified CCD camera. This allows covering the whole range between 200 and 1,000 nm, setting precisely the delay (the triggering scheme of Figure 2a can be used by assuming $\Delta t_0 \cong 0$) and integration interval, and amplifying the signal up to a factor of 10^4 . These are fundamental features for increasing the sensitivity and

performing trace analysis. However, the costs of such spectrometers are much higher than those of the compact ones described above.

Finally, handheld LIBS devices with limited performances in terms of quantification and depth profiling are available on the market. These are based on miniaturized diode pumped solid state (DPSS) lasers with high pulse repetition frequency (~ 1 kHz), very low energy (~ 100 μJ /pulse), and pulse duration of $\sim 0.1\text{--}1$ ns, which reduces the problems related with the continuum spectrum component and then they can operate without triggering.

Besides the identification of the atomic species through comparison of the actual spectrum with the spectral fingerprints of the elements listed in databases (qualitative analysis), LIBS can be used to quantify them. As for other optical emission spectroscopic techniques, the basic assumption of the quantitative analysis is that the integrated intensities of the lines emitted by a given atomic species (analyte) are proportional to the species abundance in the plasma and hence in the material under analysis. However, besides the concentration of the elements and the response curve of the spectrometer, the intensity of a given emission line depends on other factors, such as the properties of the material and the complex interactions of the analyte within the plasma region (matrix effects), properties of the latter (temperature and electron density) associated with the specific irradiation parameters (wavelength, peak intensity, and pulse duration), and self-absorption. For these reasons, the most used approach to LIBS quantification is based on the measurement of relative rather than absolute integrated intensities. The ratio between the integral of a selected peak of the element to be quantified and the integral of a selected peak of the most abundant element (internal standard) is measured and the corresponding relative concentration is derived by comparison with a calibration curve. The latter can be achieved by fitting the intensity ratio of interest, as measured for a set of samples of known composition (i.e., known weight or atomic fractions). The reliability of LIBS compositional measurements strongly depends on the emission lines, which must be selected by evaluating their spectral purity, linear range of the calibration curve, and dependence on matrix effects.

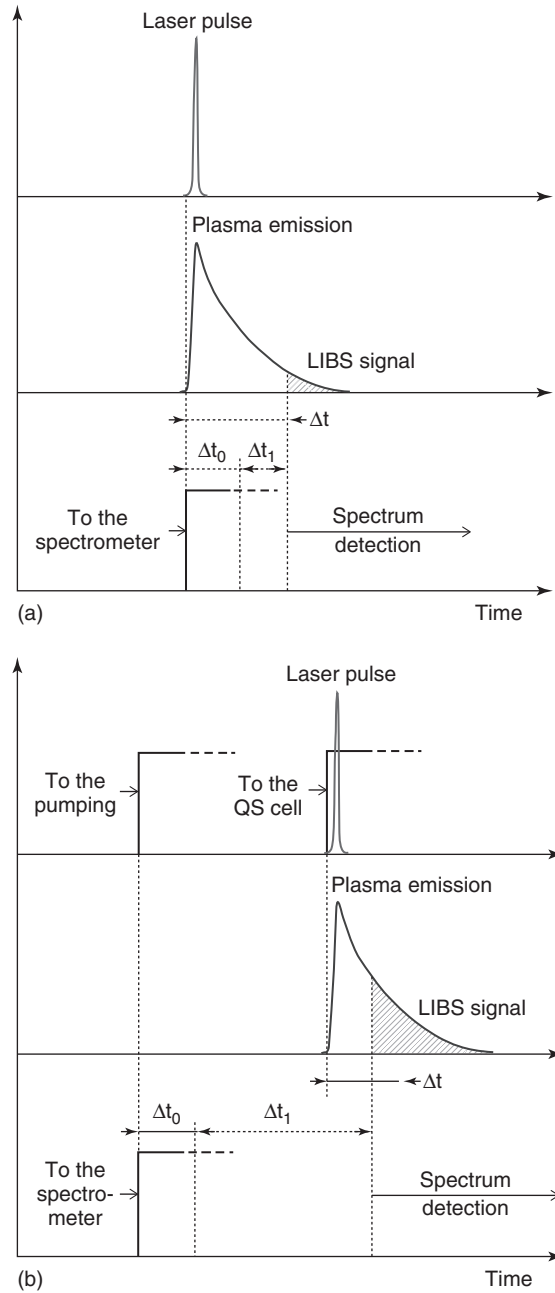


Figure 2 LIBS triggering schemes: (a) laser emission used as a master trigger; (b) spectrum detection driven by an external master trigger (see text).

When the technique is used to achieve deep elemental profiles, dependence of the calibration curves on the crater depth should be taken into account. Thus, in general, a depth-dependent calibration surface should be used in these cases.

To avoid such a careful preliminary methodological optimization work, the so-called calibration-free (CF-LIBS) method has been sometimes used (Tognoni et al. 2010). Despite the reliability of this approach being strongly

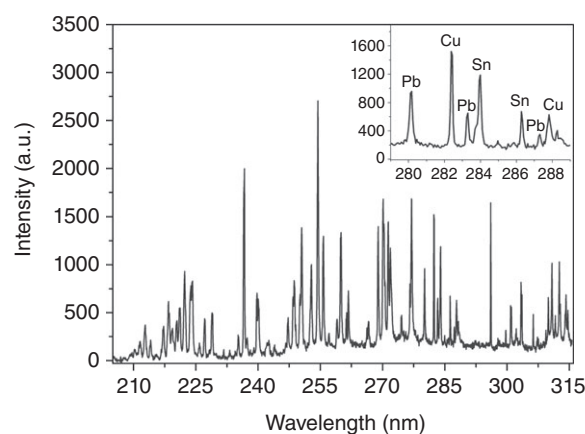


Figure 3 Example of LIBS spectrum of a bronze sample.

questioned, it can be very useful for fast semiquantitative screening of complex materials where achievement of the calibration curves using reference samples is not easily practicable.

The minimum detectable content of a given element (limit of detection, LOD) is defined as the concentration, which corresponds to an intensity of 3σ , where σ is the standard deviation of the signal produced by a congruent blank sample. When using a calibration curve, $\text{LOD} = 3 \sigma/m$, where m is the slope of its linear stretch. The LOD of elements in different materials (matrices) can be found in the literature. Such limits depend on the instrumentation and operating conditions used and can vary from parts per million to hundreds of parts per million (see for example Appendix C in Cremers and Radziemski 2013). In general, LIBS systems equipped with intensified CCD sensors provide LODs lower than the corresponding ones of devices using nonintensified sensors. Moreover, it has been demonstrated that a further improvement of the sensitivity can be achieved using two excitation laser pulses separated by a suitable delay.

Finally, the reported accuracies of LIBS are usually about 5–10 percent, which are essentially determined by the intrinsic fluctuations of plasma dynamics and of experimental conditions.

Applications of LIBS

Although the analytical potential associated with laser-produced plasmas was recognized quite

early on since the beginning of the 1960s, the complexity of early laser sources and spectrometers did not allow concrete exploitation of LIBS up until the 1980s, when the novel technique started to be used in the environmental field in order to reveal the presence of contaminants. This step was helped by the technological advances of solid-state laser sources, holographic gratings, and precisely triggerable gated multichannel optical analyzers. Since then, LIBS has been extensively tested in various fields in all those material characterization problems where other elemental techniques such as atomic absorption spectroscopy (AAS), inductively coupled plasma with optical emission spectroscopy (ICP-OES), and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) were already routinely used (Gaudiuso et al. 2010).

Early applications of LIBS in the field of cultural heritage were carried out during the early 1990s (Anglos and Detalle 2014). It is interesting to note that this applicative extension appeared almost simultaneously with the significant growing interest in the use of the laser as a conservation tool.

The main feature that has stimulated widespread applicative interest of LIBS in archaeometry concerns the possibility to perform rapid and relatively low-cost elemental analyses of any material directly on the object of interest, by avoiding invasive sampling, and time-consuming and expensive sample preparations, usually needed for traditional techniques such as AAS and ICP-OES. The minimal material ablation

involved and the availability of portable devices have made LIBS particularly attractive for archaeometrical applications, where the non-invasiveness and possibility to operate in situ can represent crucial factors whenever investigating valuable artifacts. Some of the studies reported in the literature have shown that also for the latter, exhaustive compositional maps can be achieved by collecting depth profiles from several tens of sites.

Thus, the microdestructivity does not represent a limitation in most of the cases of practical interest. As mentioned above, typical crater diameter ranges from 10 to 200 μm , while its depth strongly depends on the material under analysis. The ablation rate is a very variable parameter, ranging from the submicrometric scale of the metals to some tens of microns of the mortars. Such damage scales are usually acceptable also for relatively small artifacts, and even more when it is possible to perform the measurements in zones that are not visible in normal fruition conditions. Apart from the crater, which is almost invisible whenever LIBS is properly applied, sometimes the main problem could be due to the formation of a surrounding redeposition halo in the case of shiny surfaces. However, such a sort of stain can be minimized by reducing the energy and total number of laser pulses used, as well as completely removed with a soft mechanical action.

For archaeological objects, the redeposition effects are often negligible. Thus, within the present context, LIBS can be certainly considered a noninvasive technique (i.e., no relevant visible alteration effects are produced). This can be understood, for example, by considering that the mass needed for one traditional ICP-OES analysis of a metal alloy corresponds to some hundred LIBS depth profiles (sites analyzed) using about 2,000 laser pulses for each one.

Since the early 1990s, LIBS has been widely used for analyzing pigments, glasses, ceramics, and metals, even though the case studies reported are still relatively few. Routine material analyses for characterizing the state of conservation (see CONSERVATION) and approaching important archaeometrical problems still remain mostly based on traditional techniques, such as SEM-EDS, ICP-OES, and ICP-MS. Furthermore, the growing use of portable X-ray fluorescence (XRF) (see PORTABLE X-RAY FLUORESCENCE

SPECTROMETRY (PXRF)), which is a well-known nondestructive technique with a long development history, is not favoring the extension of LIBS within archaeometrical practice. However, the possibility of the latter to measure any element and to achieve compositional depth profiles with high depth and lateral resolutions can play a crucial role in important identification and quantitation problems.

The application perspective of LIBS for pigment recognition (see CHARACTERIZATION OF PIGMENTS) and characterization of glasses seems limited since these materials can be more easily analyzed using portable XRF and/or Raman spectroscopy (see RAMAN SPECTROSCOPY AND MATERIAL ANALYSIS). This holds also for most of the stratigraphic problems, where confocal XRF is providing interesting results, although some specific material superposition problems could justify the use of LIBS. The application perspective becomes more relevant in geochemical studies of stone artifacts, ceramics (see CHARACTERIZATION OF CERAMICS; ELEMENTAL ANALYSIS OF POTTERY; and NONDESTRUCTIVE COMPOSITIONAL ANALYSIS OF CERAMICS), and mortars (see CEMENTS, MORTARS, BINDERS) for general quantitative characterization purposes, as well as to identify the presence and assess the spatial behavior of specific elemental markers related, for example, to provenance and authentication studies or assessment of the conservation treatments. Finally, for metal alloy artifacts, LIBS offers unique performances and an exploitation perspective for investigating their complex surface deterioration stratigraphies and achieving representative bulk compositions (see DETERIORATION OF METALS and CHARACTERIZATION OF METALS AND ALLOYS). Relevance of this peculiar application has been thoroughly demonstrated in both statistical analysis of small archaeological findings (Fortes et al. 2005) and a number of archaeometallurgical studies of well-known Italian copper alloy masterpieces, such as the philosopher head of Porticello; the Arringatore from the environs of Lake Trasimeno; the Chimera of Arezzo; the bust of Emperor Antonino Pio; Alexander the Great Battling on Horseback; the sculptural groups by Giovan Francesco Rustici and Vincenzo Danti; the North Door by Lorenzo Ghiberti of the Baptistery of Florence; and

Donatello's St. Louis of Toulouse, Resurrection Pulpit, and David (Siano and Agresti 2015).

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Mass Spectrometry (MS)

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General principles

In the early twentieth century, it was observed that gas ions accelerated in a cathode tube immersed in a magnetic field were deflected and impacted the glass wall of the vacuum tube off-axis relative to the case without the magnetic field. The radius of the curved trajectory depended on the ion's mass, as follows:

$$v = \sqrt{2qV/m} \quad (1)$$

where v is the ion's velocity, q its charge, m its mass, and V the accelerating potential; the ion's deflection is governed by the Lorentz force, F :

$$F = qvB \quad (2)$$

where B is the magnetic field intensity. The Lorentz force, the vector product of v and B , is perpendicular to both. The radius r of the curved trajectory is determined by the centripetal force F :

$$F = mv^2/r \quad (3)$$

Solving for r gives:

$$\begin{aligned} r &= mv/qB \\ &= \sqrt{m/q} \times \sqrt{2V/B^2} \end{aligned} \quad (4)$$

Aston (1922), examining noble gases in a cathode tube, noticed that neon surprisingly impacted the glass wall in two well-separated spots. He called the two spots of the same place-holder in the periodic table "iso-topes", that is, sharing the same place. The discovery of isotopes (see ISOTOPES) was followed over the years by the measurements of the isotopic composition of all elements using mass spectrometers.

Not all elements have constant isotopic compositions. Their variations can be produced by: (1) enrichment of a single isotope, the radiogenic daughter, due to radioactive decay of the parent isotope (this allows age determinations by geochronology); (2) monotonic, proportional enrichment/depletion of the lighter isotope(s) relative to the heavy one(s) of one and the same element. This natural mass-dependent fractionation (MDF) can have two causes. It can be either a kinetic effect (such as the slightly faster evaporation rate of an isotopically lighter liquid, or the partial uptake by living beings of an isotopically lighter molecule) or an equilibrium effect (such as the disproportionation of heavy/light isotopes in strongly/weakly bound molecules). Isotopic variations spawned a new branch of geology around 1950, isotope geochemistry, which relies on the continuous improvement of mass spectrometers.

An essential requirement of any mass spectrometer is a high vacuum. The mean free path of an ion under atmospheric pressure is $<0.1 \mu\text{m}$, which makes it impossible for an ion to travel straight from the source to the collector. If the pressure in the evacuated apparatus is 10^{-2} Pa (10^{-7} times the atmospheric pressure), the mean free path is 1 m. This means that in a mass spectrometer with a 1 m long flight tube, every ion has, on average, one collision with an air molecule between source and collector. Ions will reach the collector, but as every collision deflects the ion in an unpredictable way, the high collision probability makes measurements irreproducible. To achieve a measurement uncertainty lower than 10^{-4} , all systematic factors that could bias the result must be kept $<10^{-5}$, including collisions with air molecules. Less than one ion in 10^5 can collide with residual air. The vacuum required to ensure this mean free path is $<10^{-6} \text{ Pa}$.

Decisive improvements to mass spectrometer design were due to Nier (1940), who improved ion sources and optimized their interaction with the magnet that deflects the ion beam. In the most general terms, a mass spectrometer consists of three components: a source, a deflector, and a collection system (Figure 1).

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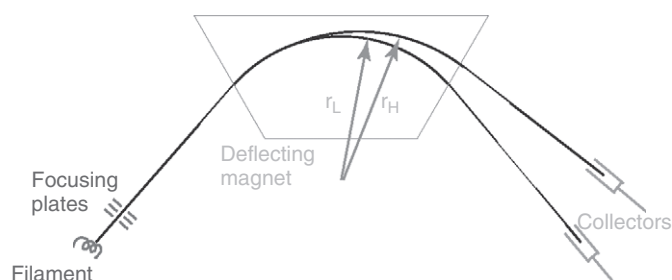


Figure 1 Schematic representation of a mass spectrometer. The ion source is drawn here as composed of an ionizing filament and a number of plates that collimate and focus the ion beam. The deflector is drawn here as a magnet that deflects the ions as given by equations (1–4). The curvature radii r_L and r_H depict the circular sector trajectories of a light and a heavy ion, respectively. The two collectors drawn here are positioned so as to simultaneously acquire the light and the heavy ion beams. The whole flight tube (not drawn here for clarity), from the source to the collectors, must be kept in high vacuum ($p \ll 1 \mu\text{Pa}$) at all times. Note that all three components (ion source, deflector and collectors) do vary from the present general sketch in the different mass spectrometer types.

The ion source

The ion source creates, accelerates, and focuses the ions of the element to be measured. Different source designs are applied to different classes of problems, according to the respective capability of a source to ionize the elements of interest. In archeometric research, gas mass spectrometers (see below) are used for oxygen, carbon and nitrogen, which help constrain paleoclimate and human diet; TIMS and MC-ICP are used for Sr, Nd, and Pb, which help constrain the provenance of artifacts (metals, ceramics) and humans; AMS is used for ^{14}C and ^{10}Be geochronology; QMS-ICP is used for trace element concentration measurements in provenance studies (see below).

The first mass spectrometers, built a century ago, were suitable for the isotope analysis of rare gases and of O, C (as CO_2), N, and so on. In gas mass spectrometers, the ion source is a hot (1500–2000 °C) tungsten filament that emits electrons, which in turn ionize the low-pressure neutral gas that enters the flight tube. The positive gas ions are accelerated by a perforated plate having a negative potential of ca. 3–4 kV relative to the filament. Focusing the ion beam is achieved by a stack of several slits and half-plates, each having a potential difference of a few to a few tens of volts relative to the neighboring ones (a design dating back to Nier). The collimated ion beam then flies into the deflector.

Two factors control the total yield of ions that reach the collectors out of the number of neutral atoms that were let into the mass spectrometer source: (1) the ionization yield of the electron bombardment can be controlled by the filament current (i.e. the number of electrons) and the energy of the electrons, which are accelerated by an additional positive electrode; (2) the transmission yield of the (initially highly divergent) ion beam is never 100%, as most ions are accelerated at an angle with respect to the trajectory that eventually leads into the collector, and are implanted into the walls of the flight tube. As the multiple bending of the ions' trajectories by the focusing plates is a function of each ion's mass, it follows that the efficiency of focusing light ions into the collector is different from that of focusing heavy ions. Therefore, as a rule, the measured N_L/N_H ratio (where N_L and N_H are the numbers of ions with light and heavy isotopic mass, respectively) is different from the true N_L/N_H ratio in the sample, resulting in an artificial MDF. This effect is an intrinsic property of all sources that accelerate and focus an initially divergent ion cloud. Typically, it amounts to a few tens of percent per atomic mass unit (amu) and can be positive (preferential transmission of heavy masses) or negative (if light masses are favored). A reasonable assumption is that a source will cause a constant MDF as long as the tuning conditions of the plate stack are not changed due to electronic drift or retuning.

In rare gas mass spectrometers, the sample introduction is relatively simple: rare gases first need to be purified completely from all active gases (water, oxygen, methane, carbon dioxide, etc.), and then are introduced into the flight tube by completely opening an inlet valve and measured “in static mode” (i.e., the gas is left in the tube during the entire measurement and is pumped away at the end). A typical rare gas analysis lasts 10–20 minutes; shorter analysis times result in excessively high uncertainties, due to the low number of counted ions, whereas longer analysis times do not add precision due to the natural instabilities of the signal, caused by fluctuations in the spatial distribution of the gas in the source. In static mode, the gas is implanted into the walls of the flight tube and exponentially depleted with a time constant of a few ks.

In oxygen-type mass spectrometers (which also measure hydrogen, carbon, and nitrogen) the amounts of gas to be analyzed are much larger than in rare gas measurements (μmol as opposed to pmol), and static measurements are impractical. The measuring protocol differs from the rare gas protocol in two very important points: (1) the sample gas is leaked into the mass spectrometer through a very thin capillary, whose flow rate is carefully calibrated; the measurement is made “in dynamic mode”, whereby the gas is pumped from the flight tube at the same rate as the inflow; (2) to maximize the resolution of small isotopic differences between samples, each unknown sample measurement is bracketed by immediately preceding and following measurements of a reference standard of known isotopic composition. The mass spectrometer is equipped with a twin inlet, consisting of two identical capillaries, one for the sample, one for the reference standard, which are automatically switched by the measuring software. Each of the sample and standard measurements lasts for about 3–5 minutes.

In order to analyze non-gaseous elements, a different source is needed. The principle of a so-called thermal ionization mass spectrometer (TIMS) relies on releasing the ions of a solid element by slow vaporization, whereby a very small amount of the element of interest is deposited onto a thin ribbon of an ultrapure refractory metal (Pt, Ta, Re or W). Heating of the ribbon, also called filament, causes some of the evaporating atoms to become ionized and to

undergo MDF similar to that described above. The ionization and the mass fractionation of an element are affected by the presence of other elements on the filament; it is therefore mandatory to chemically purify the analyte.

One useful characteristic of thermal ionization is that each element has its own, distinct ionization temperature range. As a rule, volatile elements and elements with a low ionization potential are ionized both at lower filament temperatures and more completely than refractory ones. As an example, in a Rb-Sr analysis it can occur that the chemical separation of Rb from Sr was only 99% complete. The presence of ^{87}Rb would lead to isobaric interference and to an incorrect measurement of the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio. However, fortunately for analysts, Rb is evaporated and ionized at lower filament temperatures than Sr. By a judicious choice of the filament heating protocol, all of the Rb can be boiled off before Sr emission starts, avoiding the isobaric interference.

Chemical purification of the element to be analyzed (mainly by chromatography; also by ligand extraction, distillation, or selective precipitation) leaves it as a soluble salt (chloride, nitrate, phosphate, etc.). In order to deposit the sample as uniformly as possible on the ionizing filament, the salt is taken up in ca. 1 μl of a loading solution and pipetted as close as possible to the center of the filament. As the filament is heated the ion beam will increase slowly to a maximum and remain stable for a time sufficient for a precise measurement. This time can vary between 10 minutes for a Pb analysis of single zircon grains, and over 10 hours for single-collector Nd analysis of crustal rocks. The analysis of refractory elements can be long and demanding; alternative analytical strategies require a plasma source. Some elements (e.g., Th, Hf) are exceedingly difficult to measure by TIMS, so that their use in isotope geochemistry and geochronology only became widespread after the invention of plasma sources.

Laboratory MDF can be corrected whenever the following assumptions are met: (1) natural MDF was negligibly small; (2) the element of interest has at least three isotopes, two of which are free of radiogenic daughter ingrowth and whose ratio is assumed to be fixed; or (3) the element only has two isotopes, and its MDF

behavior is identical to that of the bracketing standards.

MDF corrections use an empirical exponential law (Russell, Papanastassiou, and Tombrello 1978). The reason for resorting to an empirical correction, instead of a rigorous mathematical formulation, is that isotope fractionation is produced by concurrent but profoundly different effects: source fractionation, due to incomplete collimation of the beam by the focusing plates; Rayleigh fractionation, which occurs due to element evaporation from the filament; and inter-ion collisions. The relative importance of these effects changes as sample evaporation leads to a depletion of light isotopes in the residue. The bulk isotope fractionation in a measurement is the sum of these independent effects, each of which is sample-dependent and time-dependent.

Accelerator mass spectrometers (AMS) can be used to quantify very low isotope ratios, as are encountered in radiocarbon dating and cosmogenic isotope dating. As an example, the $^{14}\text{C}/^{12}\text{C}$ ratio of a 50 ka old sample is 10^{-15} . This requires control on systematic artifacts (e.g., tailing of the larger peaks, molecular interferences such as hydrides, etc.) of the order of 10^{-16} . This is achieved by an accelerating voltage of a few MV, provided by a tandem accelerator, and improved energy filtering of the beam.

Plasma source mass spectrometers (ICP-MS) achieve the complete ionization of a sample by a 7000–9000 K hot plasma, which ionizes all elements simultaneously. Two ICP-MS designs have evolved, in order to cope with the inherent chaotic instabilities of any plasma. They are the single-collector quadrupole (QMS) and the multi-collector double-deflecting sector, MC-ICP-MS. These design features are explained below. Both designs can be equipped with two different sample introduction systems: an aspirator-nebulizer or a laser microprobe. The former is used with previously dissolved samples; the solution can either be introduced, without further chemical processing, into a QMS (in order to determine element concentrations), or be processed first, so as to isolate a single element for isotopic composition measurements by MC-ICP-MS. The laser vaporizes a small sample volume, producing nanoparticles that are entrained by the carrier gas.

Accurate correction for mass-dependent fractionation of elements that have less than two

isotopes in a constant ratio is easier than in TIMS measurements. It involves a two-step procedure: first, the desired element is chemically purified; then, a different “dopant” element with a well-known isotopic composition and without isobaric interferences with the measurand is added to the solution. As all elements are ionized contemporaneously, the dopant provides the required constant isotope ratio. This offers a better reproducibility than measuring bracketing standards (which is limited by short- and long-term instrumental drift and imperfect chemical removal of matrix elements).

The deflector

Magnetic deflection has been in use since the 1910s. In order to transmit the ion with the desired mass into the collector, the deflection radius must be adapted, by tuning either V or B in Equation (4). Changing the accelerating voltage V often entails drifts and instabilities over several tens of seconds, whereas the hysteresis of modern electromagnets can be made shorter than 3 s. For increased resolution, a velocity filter consisting of an electric dipole deflector is inserted into the flight path before the magnet in AMS and MC-ICP-MS (“double-focusing”).

An alternative to magnets producing curved (circular sector) trajectories is the electric quadrupole. Its electric field deflects the ions into spiraling trajectories that hit the flight tube walls, except for ions having one single m/q value that follow a rectilinear path into the collector. By changing the field intensity, it is possible to successively collect any ion with any m/q value. As the quadrupole field hysteresis is $\ll 1$ ms, electric quadrupole deflectors can be made to scan the mass range of interest in the ms range. This is useful in ICP sources: plasma instabilities (which modify the transmission of ions) occur on longer timescales. The entire periodic table can be scanned in less than 1 s. The reproducibility of ICP-QMS element concentration measurements can be optimized to reach 1% by repeating the scan a sufficient number of times to average away the plasma instabilities. For isotopic composition measurements, a 1% precision is insufficient, but trace element studies have been revolutionized by this technique.

The collection system

The early mass spectrometers were equipped with a single collector, into which the ion beams were sequentially deflected by “peak jumping”. Quadrupole mass spectrometers still operate like this, as only one ionic species is transmitted for a given quadrupole field. The other instruments described above nowadays have multiple, simultaneously operating collectors, such that peak jumping is possible but no longer required.

The most widespread collector is the Faraday cup (FC), a passive component consisting of a cup connected to a high resistance (0.1–10 TΩ); when positive ions hit the cup, electron currents (in the fA–pA range) flow to compensate the charge imbalance. The resulting potential at the ends of the resistance is measured. Metrological calibrations document the high linearity, and low associated systematic uncertainty, of modern FC circuits.

The factor hampering universal use of FC collectors is their sensitivity, as the signal/noise ratio is limited by the electronic noise of the amplifier. For very weak signals (aA–fA, i.e., 10^{-10} – 10^{-14} ions per second) an active component, the ion counter (IC) or secondary electron multiplier, offers better detection limits. The IC consists of a front plate which emits electrons when hit by an ion. These secondary electrons are accelerated by a voltage of ca. 2 kV and successively hit a cascade of dynodes, producing a short-lived charge avalanche that triggers a counter. It is possible to measure count rates between a few Hz and around 1 MHz, as the background count rate can be made quite low and the signal/noise ratio correspondingly high. However, ICs also have limitations: the dynamic range is 4–5 orders of magnitude at most; their linearity is no better than 1%, and is variable over time; and the FC/IC gain depends on the measuring conditions and is difficult to determine precisely.

Perspectives

Applications are addressed in detail in other chapters. Here, potential and limitations of mass

spectrometric analyses in archaeometry are briefly mentioned.

Isotopic compositions are more suitable as negative evidence, ruling out a provenance, rather than as firm, positive identifiers, since many potential sample sources (ore deposits, food supplies, pottery clays, etc.) can share similar geological/climatic histories and therefore record very similar isotopic signatures. Provenance studies require unravelling a broad context of multiple isotopic systems, ideally supplemented by laser-ablation ICP determination of geochemically significant trace element ratios (compare with Villa, 2016).

SEE ALSO: Gas Chromatography–Mass Spectrometry (GC-MS); Isotopes; Non-Stable Isotopes in Archaeology

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Metallography

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Metallography as a science has its origins in the nineteenth century, particularly with the investigations of Henry Clifton Sorby (Sorby 1864), who first cut and polished specimens of metals and thought of etching the resulting structure to reveal their morphological characteristics. A microscope suitable for metallography is called a metallograph and the light path is arranged such that the light source impinges through the lens onto the polished metal surface and the reflected rays are then passed back through the lens where a half-silvered mirror directs the light to the eye-piece. Metallographic microscopes are usually equipped with polarizing light capabilities and often with differential interference contrast (DIC), both of which are useful in the metallographic examination of archaeological artifacts.

Metallography is extremely useful for investigations into the fabrication technology of ancient metals (Smith 1965), as well as issues related to authenticity and authentication. In the case of some artifacts, preservation goals concerning the retention of the original may preclude any invasive treatment if the artifact is extensively mineralized or precious, and many advanced techniques are available for examination of some aspects of microstructure without taking a sample at all, such as neutron radiography (see NEUTRON RADIOGRAPHY AND TOMOGRAPHY), or crystallographic texture analysis (see METALLOGRAPHY AND CRYSTALLOGRAPHIC TEXTURE ANALYSIS), which has been used to examine the microstructure of the copper axe used by the Bronze Age Iceman found in the Swiss–Italian Alps (Artioli 2007).

The practice of metallography usually involves the removal of a small sample from the object concerned. It is, however, possible to polish part of an edge or selective area of a surface of an object to obtain the desired information. Conventional

X-radiography (see X-RAY RADIOGRAPHY) can provide useful information concerning manufacturing techniques and has been of great utility in metallurgical studies of ancient iron, in particular (Scott and Eggert 2009). Structural information as to whether the object has been worked to shape or cast can be seen on an X-radiograph, and the heterogeneous nature of iron artifacts made from bloomery iron can be discerned and different components examined. In some cast bronze alloys, the dendrites can even be seen on the X-radiograph and radiographic pairs can be used to image the interior of castings, allowing casting porosity, location of core pins, spacers, or chaplets to be revealed.

Methods for removal and mounting of small samples have been reviewed by Scott (1991). Examination of the polished section can utilize the light microscope (see OPTICAL MICROSCOPY), preferably a metallograph, and samples can be placed in the electron microprobe (EPMA) for quantitative analysis, or in the scanning electron microscopy (SEM) for semiquantitative analyses or imaging; analysis usually employs energy-dispersive X-ray analysis (EDXA), while imaging may utilize either secondary electron imaging (SEI) or back-scattered electron imaging (BEI), or environmental scanning electron microscopy (ESEM), or be analyzed with X-ray fluorescence (XRF) (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)) techniques, all of which are invaluable in a comprehensive study of metallographic sections.

It is possible with large objects, or with the edges of coins, to polish selected areas of objects to examine the metallographic structure in situ, in cases where it may be impossible to cut or remove a section from the object. Microstructural features may be selectively etched or pseudomorphically preserved on metallic surfaces, which allows this technique to reveal micromorphology directly. A list of etchants suitable for archaeological artifacts is given in Scott (2011).

When mounted samples are studied, the surface of the metallic specimen should be examined first in the freshly polished state, followed by

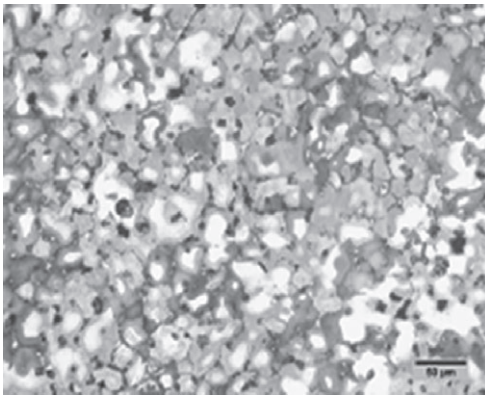
etching with a suitable etching reagent. There are often severe restrictions on the quantity of metal that can be removed from an artifact for metallographic examination, especially nonferrous metalwork. Care must be taken with very small samples to ensure that they are not lost in the process of grinding and polishing.

A number of criteria should be considered before any sampling is undertaken: (1) The microstructure of the samples should not be altered in the process of removal. (2) The sample should be representative of the object as a whole or of a selected feature or area of the object. (3) The orientation of the sample in its dimensional relationship to the object concerned should be marked on a photograph or a drawing of the object. (4) If it is not obvious from where the sample was taken, the position on the object concerned should be marked on a photograph or a drawing of the object. (5) The sample should be assigned a laboratory number together with sufficient documentation to enable its identity to be preserved. (6) The object should be photographed or drawn before the sample is taken. This is especially important if the dimensions of the object are fundamentally altered by the material removed.

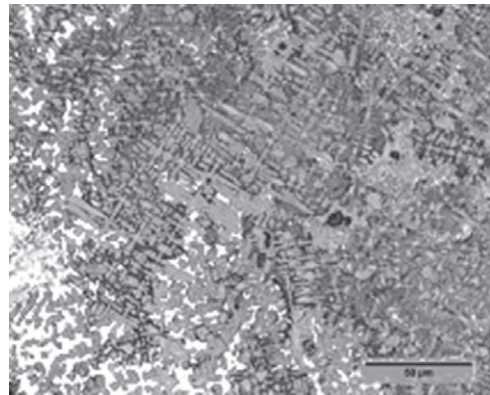
The range of features that may be made visible in prepared samples is variable, depending on the type of specimen examined and how it is prepared; detail not apparent using one etchant may become visible only after another reagent has been employed. The following are some of the major microstructure features that can be examined: (1) The range and the type of grains present. Their size can be compared with an eye-piece marked with grain sizes for comparison or with American Society for Testing Materials (ASTM) standard grain size numbers. ASTM grain size numbers range from 10 (very small) to 1 (large). Further details concerning grain size are discussed by Vander Voort (1999). The ASTM has produced a very useful reference document which should be consulted for further information (ASTM 2009). Any cracking, loss, or inclusions present at grain boundaries should be noted. (2) The presence of different phases which can be observed either in the corrosion crust or the metal. The presence of different phases is an indication of how the overall composition of the artifact relates to its actual microstructure. Gross

heterogeneity or differences between various areas of the sample should be noted, especially in the case of iron and steel artifacts. The order of magnitude of the scale of these differences may range from several millimeters to a few tens of microns. (3) The grain shapes or surface deformation features or heat-treated zones at cutting edges and worked surfaces. Metals are crystalline solids and the grains may preserve indications as to how they have been treated or affected by heat. (4) The distribution of inclusions, weld lines, slag particles, or porosity and the volume fraction of pores and holes. (5) The presence of any surface coating or gilding. Sometimes, careful examination at high magnification is necessary to establish the presence of surface coatings, lead gilding, amalgam gilding, tinning, and so on. (6) The distribution of any corrosion products present and the existence within corrosion layers of pseudomorphic remnants of grain structure or other microstructural features, remnant metallic grains, and layering or unusual features. (7) Indications of grain-boundary thickening or precipitation of another phase either within the grains themselves or at the grain boundaries. (8) The presence of twin lines within the grains and whether these are straight or curved. In face-centered cubic metals, such as copper, silver, and gold alloys, these are common. (9) The presence of stain lines within the grains; these are common in copper and bronze alloys. (10) Whether dendrites (a structure that is common in cast alloys and which may look like an intersecting snowflake pattern) shows indications of coring and the approximate spacing, in microns, of the dendritic arms, if these are clearly visible. (11) The size and shape of any nonmetallic inclusions present in the metal. Most inclusions cannot recrystallize at the temperatures at which archaeological metals are worked or cast, usually less than 1,200 °C, and they become elongated or broken up along the direction of working of the metal. (12) The presence of intercrystalline or transcrystalline cracking in the polished section. This is frequently related to working techniques employed during manufacture, or subsequent stresses experienced by the artifact as a result of burial or corrosion.

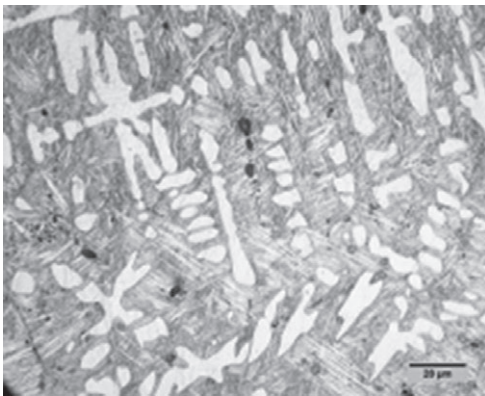
Further details concerning many aspects of metallographic preparation can be found in Scott (2011) and Van der Voort (2004). Color etching



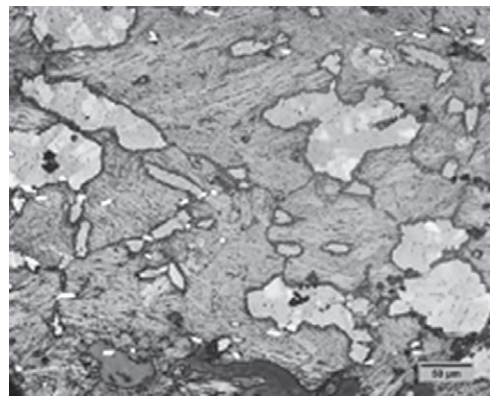
(a)



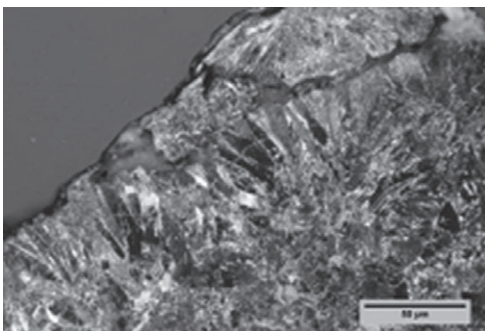
(b)



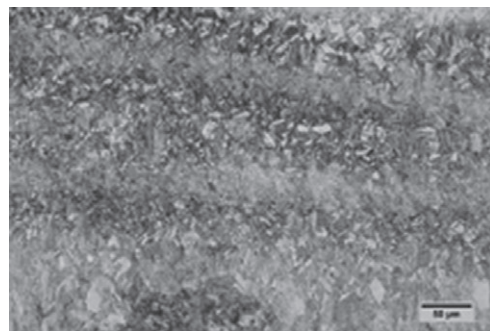
(c)



(d)



(e)



(f)

(Scott 2014) may be particularly revealing for the metallography of ancient metals, because the technique is especially good at helping to preserve the corrosion crust, often etched away in conventional etchants, and for revealing effects of segregation, which many ancient metals exhibit.

Metallography and microstructure

Some examples of the application of metallography are given here. The cross-section of a Luristan dagger from Iran reveals the extent of the differences between the hilt of the dagger itself, seen in Figure 1a, which is embedded in the cast-on bronze handle shown in Figure 1b. An extensive amount of corrosion has occurred between the junction of these two components, resulting in large amounts of redeposited copper. The casting-on process has annealed and partially recrystallized the hilt of the bronze blade, which can be seen in Figure 1a. The pronounced dendritic segregation of the higher-tin bronze alloy used to make the handle can be clearly seen in Figure 1b.

Figure 1b shows a low-magnification view of the handle itself. It is a typical cast high-tin bronze microstructure which clearly illustrates the dendritic segregation of the melt. The arms of the dendrites are copper-rich and are cored, with darker etching zones around the perimeter of the dendrites. These etch darker here because the tin content is higher than in the center of the dendrite arm. Surrounding the dendrites is an extensive infill of the $\alpha + \delta$ eutectoid phase of the bronze, which etches a pale blue-gray.

Examples of Thai high-tin bronzes are shown in Figures 1c and 1d, revealing not only the complex microstructure of these bronzes, but also the survival of the metastable beta-quenched acicular phase within the corrosion crust of these bronzes for over 2,000 years. The revelation here is that these high-tin bronzes were shaped by hot-working and were quenched from about 700 °C in order to retain the beta phase of the bronze system and to prevent the precipitation of the $\alpha + \delta$ eutectoid, which while chemically the same in terms of overall bronze composition, would give completely different working properties. The $\alpha + \delta$ phase precipitation results in the slow-cooled bronzes

Figure 1 (a) Color-etched photomicrograph of a Luristan bronze dagger and hilt. Composition of the dagger itself is 83.6 percent copper, 13.5 percent tin, 0.3 percent iron, 0.8 percent lead, 0.4 percent arsenic, 0.6 percent nickel, with zinc and silver not detected. This is an excellent choice as too much delta phase would make the blade hard but brittle. (b) Color-etched photomicrograph of a section through the cast-on handle of the same dagger. Small clumps in the structure which can just be seen here are redeposited copper. Uncorroded eutectoid appears white while corroded eutectoid is a darker gray. Composition is 76.6 percent copper, 20.8 percent tin, 0.9 percent lead, 0.5 percent nickel, with zinc, iron, and arsenic not detected. (c) Color-etched photomicrograph of a copper alloy bowl from the site of Ban Don Ta Phet, Thailand, showing dendritic alpha phase with infill of acicular beta. Microstructure reveals the bowl is cast, reheated, and then quenched. Composition is 21 percent tin, 79 percent copper. (d) Color-etched section through a bronze bowl from Ban Don Da Ne, Thailand, from the Bronze Age, showing the acicular beta phase, and twinned alpha in a background of beta phase. There is a considerable scatter of white copper sulfide inclusions present. Composition about 20.5 percent tin, 79.5 percent copper. Twinned alpha phase here reveals that the bowls have been cast, reheated, quenched, hot worked, and then quenched again, before turning on a lathe to produce the cut decoration seen. (e) Photomicrograph of an electrotyped artifact in the collection of the Victoria and Albert Museum, London, showing directional solidification and long columnar grains which often characterize copper and copper alloys deposited from solution; compare with Figure 1f. Etched in alcoholic ferric chloride, composition is 100 percent copper. (f) Electrotpe from the 1880s in the collection of the Victoria and Albert Museum. Etched in alcoholic ferric chloride, showing a series of rather fine twinned grains. This is not the usual kind of morphology associated with electrotyped copies and shows the considerable variation which is possible.

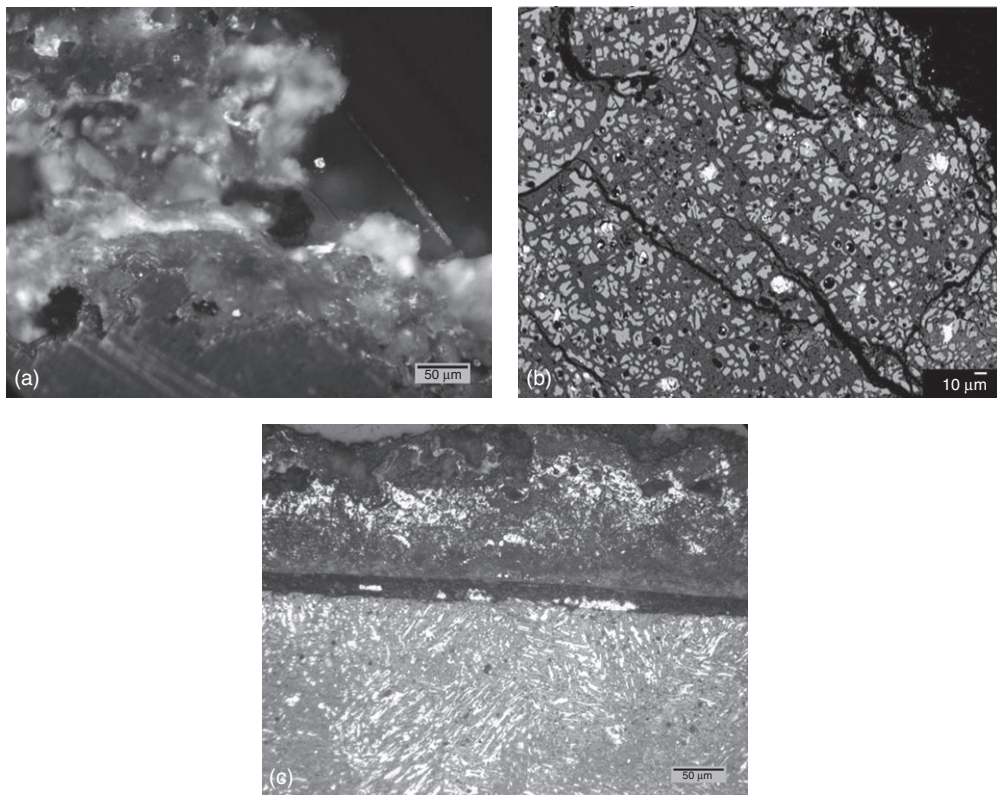


Figure 2 (a) Polarized light view of a photomicrograph of part of the surface of a copper plaque from collections of the Johan von Wagner Museum, Stuttgart. The mid-gray of the cuprite, its penetration into the remaining copper, and the outer lighter gray corrosion products of malachite are all acceptable for authenticity of the plaque. Unetched section. Composition of the plaque is 98 percent copper, with small amounts of arsenic, lead, nickel, and antimony. (b) Scanning electron photomicrograph taken on a Cambridge Instruments electron microprobe showing the remnant metallic structure of a Chinese bronze mirror of the Tang dynasty, composition 77 percent copper, 21 percent tin, and 3.5 percent lead. Bright white spots are of uncorroded lead, dark black spots are corroded lead, light gray are alpha regions and some cuprite, darker gray background is the corroded eutectoid phase of alpha + delta. (c) Cross-section through a Chinese bronze mirror from the Warring States, composition 24 percent tin, 4 percent lead, 72 percent copper. Color etched to show the fine microstructure of the alpha and alpha + delta eutectoid. An advantage of this etching procedure is that it preserves the corrosion crust rather than attacking it, allowing the entire structure to be seen under polarized light.

being very brittle. The quenching of these high-tin bronzes enabled them to be cut with a lathe and turned, which is also not possible with the normal high-tin bronze alloys.

Artifacts produced from copper solutions as electrotpe copies of the original were often made in the period 1850–1910 as exact replicas of metallic or other artifacts. It may be possible to distinguish these copper replicas from original artifacts using Laue back-scattered X-ray

diffraction techniques which produced a series of Debye–Scherrer rings with many electrotypes due to the very small grain size of deposited copper. It is the grain structure of these artifacts that is essential here, and this can be determined by metallography. The lowest energy deposition methodology for copper deposited from solution is to produce a series of columnar grains, with twinned grains common, and often occurring across the contiguous columnar crystals.

Figure 1e is a good example of directional precipitation of copper from solution in an historic electrotype from the Victoria and Albert Museum made around 1870. This structural morphology is never found in ancient copper alloys, and is distinctive for an electrotype copy.

Figure 1f illustrates the microstructure of another electrotype from the Victoria and Albert Museum, in which the twinned crystal structure of the object dominates the matrix of the deposited grains.

An interesting case is that of a Greek plaque from the ninth century BCE, of considerable importance for the history of the development of the alphabet. The plaque is made of quite pure copper, and has preserved pseudomorphic mineralized wood fragments on the surface. These can also be seen in a more rudimentary form in metallographic cross-section and are potentially important associations with the burial context of the plaques. Figure 2a illustrates a polarized light view of part of the corrosion crust of one of these plaques. The use of criteria based on the corrosion products in terms of providing evidence of authenticity has been studied since the 1950s.

Corrosion may penetrate considerably into what appears superficially to be a quite sound metallic matrix. A good example is shown in Figure 2b: a high-tin bronze Tang mirror. In the uncorroded state these mirrors frequently display a Widmanstätten precipitation of the eutectoid phase, which does not conform to the remnant microstructure seen in Figure 2c. Figure 2c does not reveal this kind of microstructure. From this we could conclude that the optimal microstructure was not attained in this example, and that it displayed more of the alpha phase in a principally cast orientation, even if not dendritic.

The fabric of the mirror shown in Figure 2b has been seriously weakened by corrosion so that parts of the artifact are prone to crumble at the edges. Figure 2c shows the etched microstructure of a mirror from the Warring States, where there is a residual Widmanstätten pattern to the delta phase, set in a rather corroded alpha matrix. Just at the boundary between the original surface of the bronze and the overlying corrosion products, some small patches of redeposited copper can be seen, a common feature in many ancient Chinese artifacts. The Widmanstätten morphology here is

due to the cooling rate of the bronze as well as its composition. Bronzes with 25 percent tin often crystallize as a cellular structure rather than a collection of dendrites.

Metallographic studies should be integrated as far as possible with archaeological data, provenance, chemical composition, and technology of manufacture to extract the maximum benefit from the removal of a small sample from the object.

SEE ALSO: Characterization of Metals and Alloys; Conservation of Metals; Deterioration of Metals

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Microarchaeology

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Microarchaeology is the study of the microscopic archaeological record, that is, everything that cannot be seen by the naked eye and therefore requires the use of instrumentation. Initially used in a purely archaeological acceptance to indicate the description of small, but visible fragments of cultural material, the term “microarchaeology” now refers to a branch of archaeology that was developed since the 1980s as a result of the application of analytical methods to the characterization of archaeological materials and sediments. This approach stems from the integration of the natural sciences with archaeology aimed at solving archaeological problems, and is based on immediate on-site analyses during fieldwork and detailed laboratory work, geared towards a better understanding of past human behavior.

Since the 1940s, the need for more detailed determinations of archaeological activity areas and building functions brought archaeologists to work on progressively smaller fragments of cultural material, such as food remains or chips resulting from the breakage and use of tools and architectural features. These fragments of waste material are embedded within occupational debris on living surfaces and in most cases undergo little displacement through trampling or post-depositional processes. For these reasons, small fragments were supposed to be the only cultural remains in primary deposition, and therefore truly representative of the human activities that took place at a specific location (e.g., Cook and Treganza 1947). In the following decades the collection methods saw improvements, and the term “microarchaeology” appeared in the early 1970s to define the study of minute fragments of artifacts and other cultural material recovered through sieving and flotation of sediments from occupational deposits (e.g., Archaeology Correspondent, 1973). However,

this subdiscipline of archaeology deals mostly with the visual identification and quantification of small remains (usually larger than one millimeter), and not with their chemical characterization in relation to the depositional context and ultimately the human activities that produced them. In fact, it is known today as “microartifact analysis” (Sherwood 2001).

Recently, “microarchaeology” became the standard term to define the study of the archaeological information hidden within sediments and artifacts, at the microscopic scale and below, with the aid of instruments such as microscopes and spectrometers. This change in meaning did not evolve from an improvement of microartifact analysis; rather, it is the result of a tradition of scientific archaeology that finds its roots in nineteenth-century Denmark. There, C. J. Thomsen and J. J. A. Worsaae developed the three-age system and the chrono-typology of artifacts using a scientific, predictive method that can be reproduced with different materials in different geographic areas. Their approach complemented work of G. Cuvier, C. Lyell, and J. Lubbock based on the principles of paleontology, geology, and evolution, thus laying the foundations of modern archaeology (Trigger 1989). However, despite chemists analyzing ancient artifacts since the eighteenth century, the scientific approach had little impact on archaeological method and theory until the mid-twentieth century. This situation changed completely with the radiocarbon dating revolution brought about by W. F. Libby (Libby, Anderson, and Arnold 1949). This global breakthrough in archaeology not only provided an independent check for relative chronologies based on chrono-typology of artifacts and ancient texts, but also created absolute chronologies. Moreover, it built a strong bond between the natural sciences and archaeology, and thus promoted the application of a large number of analytical methods to the study of archaeological materials, in particular those belonging to the microscopic record. For instance, since the late 1970s special attention has been devoted to the study of microstratigraphy using sediment micromorphology

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(see MICROMORPHOLOGY) and X-ray diffraction (XRD), in order to better characterize natural and anthropogenic formation processes (see FORMATION PROCESSES). It is within this framework that present-day microarchaeology was established by S. Weiner in the 1980s, with the first systematic studies of mineral and bone assemblages in prehistoric cave sediments using an on-site laboratory (Weiner and Goldberg 1990). At the same time, microarchaeology gained momentum from its overlap with the field of biomineralization, which focuses on understanding the processes used by organisms to mineralize their tissues (Lowenstam and Weiner 1989). Phytoliths, bones, teeth, dung spherulites, mollusk shells, eggshells, and diatoms are all biominerals commonly found at archaeological sites. They are often directly related to human activities, and in some cases they record paleoenvironmental settings. Thus, the ability to identify and describe these components, and how they end up in archaeological deposits, is a crucial step for the correct interpretation of archaeological contexts and past human behavior. The interaction between microarchaeology and biomineralization dramatically expanded the amount of information that can be obtained from the archaeological record. At present, microarchaeology has been successfully employed at several sites from different periods and regions of the world.

The goal of microarchaeology is to answer archaeological questions by extracting information from the archaeological record below the submillimeter scale. This includes the materials of which the macroscopic artifacts and archaeological features are made, as well as the sedimentary matrix in which the artifacts are found. To do so, microarchaeology makes use of analytical methods that address different aspects of the microscopic record, depending on the research question at stake. Such methods encompass, but are not limited to, the techniques employed in archaeometry (see ARCHAEOOMETRY), geoarchaeology (see GEOARCHAEOLOGY and SOIL CHEMISTRY IN ARCHAEOLOGY), paleogenetics (see ZOOARCHAEOLOGY AND ANCIENT DNA and DNA: NEXT GENERATION SEQUENCING), archaeobotany (see PALEOETHNOBOTANY; PALEOETHNOBOTANY AND ANCIENT DNA ANALYSIS; PALEOETHNOBOTANY AND STABLE ISOTOPES; and PALYNOLOGY), zooarchaeology (see ZOOARCHAEOLOGY;

ZOOARCHAEOLOGY AND HUMAN DIET RECONSTRUCTION; ZOOARCHAEOLOGY AND HUMAN TRADE AND MIGRATION; and ZOOARCHAEOLOGY AND STABLE ISOTOPES), geochemistry (see HUMAN SKELETAL GEOCHEMISTRY and PALEOENVIRONMENTAL RECONSTRUCTION), and absolute dating (see DATING IN ARCHAEOLOGY), and are aimed at reconstructing the formation processes of archaeological contexts (see FORMATION PROCESSES), the manufacturing processes of artifacts, and their transformations due to post-depositional alterations (see TAPHONOMY). Particular attention is dedicated to the study of diagenesis (see DIAGENESIS OF BONE), which may alter the original mineral assemblages of sediments and artifacts and therefore lead to misleading interpretations. Only pristine organic and mineral components may be used for archaeological purposes. On the other hand, the absence of specific minerals or categories of artifacts, such as bone, or the presence of diagenetic minerals, can help determine whether archaeological contexts are affected by diagenesis, which in turn might be driven by changes in environmental conditions of archaeological importance. Results are then integrated with the information obtained from the study of the macroscopic record (architectures, artifacts, bones, burials, installations, etc.) to reach a better understanding of past human activities and therefore of the archaeological record as a whole.

The macroscopic and microscopic records are part of the same entity, and, as such, they should be investigated at the same time. Therefore, as with all archaeology, microarchaeology starts in the field with the identification of an archaeological problem. In order to answer a specific question, data are gathered during excavation, analyzed, and in light of the results, the original question is reformulated, according to a scientific method. Considering that archaeological excavations are destructive operations, it is useful to characterize the relevant contexts before they are removed using an on-site laboratory, which can provide results within minutes or hours, depending on the method. This is a key step in microarchaeology, as it provides invaluable contextual information regarding the archaeological problem that would otherwise go lost. It also helps in reducing sample size and costs, as opposed to “blind” sampling of the entire

site. In addition, it forces archaeologists with different backgrounds (macro versus micro) to discuss problems and the strategy to tackle them, and confront each other as work is in progress, finding a common basis for communication. By spending weeks together in the field, experts in the microscopic record can understand all the subtleties regarding archaeological contexts, whereas experts in the macroscopic record realize the potential applications and limits of analytical instruments. The setup of the on-site laboratory may include a Fourier transform infrared (FTIR) spectrometer for the qualitative characterization of chemical phases in artifacts and sediments (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)), a bench X-ray fluorescence (XRF) spectrometer for the quantification of metallic compounds (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), a petrographic microscope for the analysis of mineral and organic components in sediment smear slides (see OPTICAL MICROSCOPY), a binocular microscope for the analysis of microartifacts, a dry-sieving apparatus for the recovery of small charred materials, and the gear for phytolith and phosphate extraction (see PHYTOLITH ANALYSIS and SOIL PHOSPHATE CHEMISTRY, respectively). Results are obtained in real time and interpreted in comparison to a set of control samples that help in differentiating the archaeological context under investigation from the sediments surrounding it. These results contribute to a better overall understanding of the site. With this new information, the original question can be refined or rejected, and the excavation strategy is adjusted accordingly. A new round of sampling may be carried out for immediate analysis, or a full set of samples may be collected for more detailed research at the home laboratory after the end of the excavation. There, samples may be analyzed using time-consuming methods such as sediment micromorphology (see MICROMORPHOLOGY), and nonportable instruments that can provide characterizations at the molecular and atomic level, such as XRD, Raman micro-spectrometry (see RAMAN SPECTROSCOPY), FTIR micro-spectrometry (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)), scanning electron microscopy with energy dispersive spectrometry (SEM-EDS), mass spectrometry for stable isotope analysis, accelerator mass spectrometry for radiocarbon

dating, gas chromatography-mass spectrometry (GC-MS) for the analysis of organic residues (see ORGANIC RESIDUE ANALYSIS), and thermogravimetric analysis (TGA). The choice of methods and instruments should be tailored to the original research question.

Besides answering specific archaeological questions, laboratory work may lead to major discoveries. The occurrence of apparently inconspicuous or previously unnoticed components and features in sediments and artifacts may trigger the development of new analytical procedures, or the improvement of established methods, with fundamental implications for both the natural sciences and archaeology (e.g., Regev et al. 2010; Toffolo and Boaretto 2014). In this sense, microarchaeology is a constantly expanding discipline, with much room for improvement. Progress takes place not only through technological advancements in instrumentation developed for other disciplines, such as geochemistry and biology, but also with the application and refinement of known procedures, thanks to the diversity of the archaeological record. With a growing demand for better precision and accuracy in the characterization of archaeological materials, it can be predicted that in the near future new methodologies will be developed specifically to solve archaeological problems. This will be the result of training archaeologists in both the natural sciences and archaeology, who will be able to study the archaeological record in its entirety, going from the macroscopic to the microscopic and back.

SEE ALSO: Archaeological Fieldwork; Archaeometry; Archaeomineralogy; Chemistry in Archaeology; Ethnoarchaeology; Experiment in Archaeology; Formation Processes; Geoarchaeology; Nanoarchaeology; Soil Chemistry in Archaeology

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Micromorphology

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Micromorphology is the study of undisturbed samples of soil, sediment, and archaeological materials (e.g., adobe) at the microscopic level (Courty, Goldberg, and Macphail 1989), generally using polished slabs of the material and petrographic thin sections (see OPTICAL MICROSCOPY). The fundamental essence of the technique relies on the fact that the context and the original position of the components are preserved, permitting the identification of primary (depositional) events and processes (e.g., sedimentation of natural or human origin) from post-depositional ones, such as soil formation (and its associated processes), human trampling, or remobilization of the material being studied.

Micromorphology has its roots in soil science, dating to the publication of *Micropedology* by Kubiěna (1938), which sets out a series of guidelines for systematically observing and describing the coarse and fine components in the soil in order to understand soil genesis. Since the late 1930s and into the 1980s, micromorphology was generally practiced by soil scientists who concentrated on soil genesis/classification, mineral weathering, paleopedology, and agriculture, among others (Stoops 2014). Although Cornwall (1958) was among the first to use micromorphology in an archaeological context, it was not until the 1980s that micromorphology really began to be applied to archaeological issues (Courty et al. 1989). Its overall practice in soil science has declined since the beginning of this century, although its use in archaeology and sedimentology has increased substantially during this interval (Stoops 2014).

“Archaeological micromorphology” (which is the implied use for “micromorphology” in this entry) has a more inclusive approach than that of “soil” micromorphology: It is broader

in scope and examines geogenic and anthropogenic deposits, and archaeological materials (e.g., adobe, mortars, plasters), and its goals comprise—among others—landscape and paleo-environmental reconstructions, human constructions, past human activities, past behaviors (e.g., agricultural practices, pastoralism), pyrotechnology, and the suite of physical and chemical changes that modify archaeological deposits (diagenesis); many of these processes in aggregate can be subsumed under the rubric of “archaeological site formation” (see FORMATION PROCESSES).

Whatever the goal, micromorphological investigations start with thorough, well-documented fieldwork, especially careful examination and documentation of the site’s context, geomorphic setting, and site microstratigraphy (see ENVIRONMENT AND LANDSCAPE; ENVIRONMENTAL ARCHAEOLOGY; and GEOARCHAEOLOGY); good field photos of the deposits showing location of the micromorphological and associated samples help guide thin section observation and interpretation. Archaeological deposits are complex and exhibit a large amount of vertical and lateral lithological variability and interstratification at a site or within a structure, particularly when the anthropogenic components and human activities are prevalent, such as in Neolithic and later period sites—tells and mounds. In order to account for this inherent variability in the field, Courty (2001) extended the concept of facies from geology to include that of microfacies, which helps keep track of localized differences in depositional and post-depositional processes. In doing so, it provides a bridge from field observations to those made under the microscope.

In light of the undisturbed nature of micromorphological samples, the original geometry of the components (both solids and voids) has to be maintained. These blocks can be collected in several ways (Goldberg and Macphail 2006): (1) cutting them out from a profile of compact material and wrapping them tightly with tissue and tape; (2) inserting drainpipe or metal boxes into a section (so-called Kubiěna boxes); or (3) encasing the blocks with bandages impregnated

with plaster of Paris. In the laboratory, the unwrapped blocks are either air- or oven-dried (generally around 40–60 °C) for several days; for clayey materials, water may be removed by freeze-drying or acetone replacement. The sample is then impregnated with resin—typically epoxy or unpromoted (i.e., accelerator-free) polyester resin—preferably under vacuum in order to ensure better penetration of the resin into the sample, particularly for clayey samples. Good results can be achieved for nonclayey samples after a gel-time of just a few days. The hardened blocks are then sliced with a rock saw and appropriate areas within the slices are selected and trimmed to the final appropriate size of the thin section. Unlike slides typically used in sedimentary petrography (27 × 46 mm), those in archaeological micromorphology are larger so as to incorporate the inherent heterogeneity of archaeological deposits and features within a slide. Dimensions of finished thin sections vary from 50 × 75 mm up to 140 × 68 mm. The trimmed blocks are ground flat on one surface, glued to the thin section, and then ground and polished to a thickness of 30 µm. The thin sections are left uncovered to permit subsequent analysis by other microanalytical techniques (Goldberg and Macphail 2006).

In tandem with the collection of blocks, small bulk samples (~200 g) are collected from microstratigraphic units for other analyses (e.g., X-ray diffraction (XRD), bulk chemistry) (see RAMAN SPECTROSCOPY). As a caveat, in measurements from bulk samples, one is not certain what is being analyzed: calcite from original deposition of limestone versus secondary precipitation of calcite from roots, or speleothems.

Thin sections are studied optically with stereo- and petrographic microscopes at magnifications from 1 to 500× using plane-polarized (PPL), cross-polarized (XPL), and dark field illuminations; ultraviolet (UV) and cathodoluminescence are particularly useful tools for examining diagenesis. Whereas petrographic microscopes are needed to document mineralogy or small components such as phytoliths, low-magnification observation is essential to document the microstructure and the organization of the different materials in the sample, that is, the fabric, and the thin sections should be

observed alternately and repeated at these different microscopic scales. A good flatbed scanner can produce high-resolution scans of both the thin sections and the polished slabs from which they are made. In addition, thin sections or parts of the slabs can be studied with scanning electron microscope (SEM) or electron microprobe at several thousand times magnifications to examine crystallinity, diagenesis, and elemental composition (see DIAGENESIS OF BONE AND ELECTRON BACKSCATTER DIFFRACTION (EBSD)).

Micromorphological observations are similar to those used in sedimentary petrography and should be comprised of objective attributes. For coarser grains (i.e., sand, larger sizes) these include mineralogical and organic composition, abundance, size, and shape of grains, and sorting (distribution of grain sizes). For the finer matrix (generally silt and clay) the internal organization is noted (b-fabrics), which in XPL is displayed by the birefringence and extinction patterns: well-oriented clay, for example, will show parallel extinction, whereas randomly oriented particles will have a speckled appearance. At a higher level of observation is the porosity/microstructure (e.g., crumbly, platy, etc.).

In addition to these individual components and fabrics are features that are essential to understanding the history of a deposit. (1) *Sedimentary features* concern sediment source, mode of transport, and deposition of clastic grains. Deposition creates sedimentary structures, such as bedding and surface features (e.g., ripple marks). (2) *Pedologic and post-depositional features* refer to modifications of existing materials by biological, mechanical, or chemical processes. Examples include aggregation of material by burrowing or as excrements, coatings of clay in voids or around grains, and the precipitation of oxides, carbonates, and phosphates in voids or as nodules. (3) *Anthropogenic features* are produced by human activities and represented by ashes, charcoal, bone, organic matter, lithics, pottery, and construction materials; at a higher order of organization these can take the form of hearths or walls, for example.

Since archaeological deposits are lithologically highly variable, a single thin section can be quite complex and many differences can be observed from top to bottom, commonly occurring as

microstratified layers (i.e., on the order of centimeters) of different compositions, structures, and so on. In addition, some of the layers may be present in different thin sections from the same vertical sequence or in different parts of the site. Thus, it is best to try to categorize these layers into microfacies in the sense of microstratigraphic units visible and definable within a thin section (Flügel 2009). Applying this concept obviates the need to describe the same units repeatedly and at the same time significantly improves the ability to interpret the deposits as a whole, both from within a thin section and up to a reconstruction of formation processes at the site scale.

At the interpretative level, the microscopic observations as an ensemble can lead to a comprehensive understanding of the sum total of geogenic and anthropogenic deposition, as well as physical and chemical post-depositional processes. The former might include trampling, reworking of sediment by dumping, middening, or hearth formation and cleaning, whereas the latter might entail dissolution of limestone or bone, or the precipitation of secondary minerals such as phosphates that reflect diagenesis and environmental conditions at the site.

It should be emphasized that micromorphological investigations of thin sections using optical microscopes are just the starting point, and there are analytical limits governed in part by the thickness of the thin section and the size of grains. Although SEM/microprobe has traditionally been used to assess mineralogical and elemental composition, more recent approaches make use of the context preserved in the thin section to analyze specific grains and make inferences of the temperature of heating of bones and clays, for example, types of organic matter, and so on. Techniques include micro-Fourier transform infrared (FTIR) and Raman spectrometry, micro-X-ray fluorescence (XRF) and XRD (Mentzer and Quade 2013).

This “in-situ analysis” is a relatively recent development and it illustrates one of the major advantages of micromorphology: the original “micro” context of all components is preserved and can be related to their actual position in space (the microcontextual approach of Goldberg and Berna 2010). Micromorphology in this way serves as a methodological filter whereby thin section observations point the way to subsequent

specific analyses to answer questions not resolvable with optical microscopy (e.g., what is the mineralogy of a certain precipitated mineral or grain—aragonite versus calcite?).

Lastly, in addition to new analytical instruments and methods, ethnological approaches have been used to improve the quality of micromorphological interpretation (e.g., Shahack-Gross 2011) (see ETHNOARCHAEOLOGY). All of these approaches further our ability to understand the natural and human history occurring at an archaeological site.

SEE ALSO: Chemical Mapping;
Coprolites; Dating in Archaeology;
Deterioration of Earthen Building Materials;
Diagenesis of Bone; Electron Microscopy
in Conservation; Experiment in Archaeology;
Glacial and Periglacial Environments;
Imaging; Microarchaeology; Phytolith Analysis;
Pyrotechnology of Cements; Taphonomy

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Mössbauer Spectroscopy

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In the first half of the twentieth century, the nuclear emission and absorption of γ -rays, leading to subsequent γ -ray fluorescence, was only predicted but not demonstrated. The main difficulty in experimental demonstration was due to the existence of the nuclear recoil, which accompanies both the γ -ray emission and absorption in free nuclei. In fact, the energy involved in the nuclear recoil process inhibits the resonant absorption in a free nucleus, and therefore γ -ray nuclear fluorescence cannot be revealed. In 1958, a young scientist, Rudolf Mössbauer, published his first paper demonstrating that a nucleus in a solid matrix can sometimes emit and absorb γ -rays without recoil. In a solid matrix the nucleus is no longer isolated, but is fixed in the lattice, which minimizes the recoil process. In this condition, nuclear resonance fluorescence can be detected. This phenomenon, known as the Mössbauer effect, or recoilless nuclear resonance fluorescence, is the core of Mössbauer spectroscopy (MS). In 1961, Mössbauer, at the age of 32, was granted the Nobel Prize for his work on recoilless nuclear resonance.

The occurrence of a recoil-free event depends not only on the vibrational properties of a solid, but also on temperature, nuclear lifetime, and energy of the nuclear γ -ray. The last phenomenon delineates the Mössbauer effect only to a certain nuclide. These nuclides should possess excited nuclear states with lifetimes in the range of ca. 10^{-6} to 10^{-11} s, and transition energies between ca. 5 and 180 keV. ^{57}Fe is the most suitable nuclide; other frequently used nuclides are ^{119}Sn , ^{121}Sb , ^{123}Eu , and ^{197}Au . Investigations on nuclear resonance fluorescence led to the development of nuclear spectroscopy. MS probes slightly change the energy levels of a certain nuclide as a consequence of the interactions between the nuclide itself and its chemical environment. MS provides

both chemical and structural local information about a specific nucleus embedded in a solid matrix. It is a solid-state technique and it is used as an investigation tool in most of the disciplines of natural and applied science, such as nuclear physics, chemistry, mineralogy, metallurgy, and, of course, archaeometry.

In the traditional setup, the spectrometer is formed by two basic components: a proper source of γ -rays and the detector, usually a proportional counter or a scintillator. The solid sample, conveniently powdered, is placed between the source and detector. In order to have the effect, the source and sample (defined also as the absorber) contains the same Mössbauer active nucleus. That is, different absorbers need different sources: An ^{57}Fe absorber needs a source that can generate γ -rays with the proper energy to promote nuclear resonance fluorescence. With ^{57}Fe , the source is ^{57}Co , which transforms, by electron capture, in the metastable ^{57}Fe in the $5/2$ nuclear excited state. The thus-generated excited nucleus decays spontaneously to the $1/2$ ground state via a γ -ray cascade which includes the decay from the excited $3/2$ level to the ground level. This process emits the 14.4 keV γ -radiation necessary to excite the ^{57}Fe nuclei in the absorber from the ground state to the $3/2$ excited state, giving rise to the Mössbauer effect. A similar process is involved for other nuclides. The γ -rays not absorbed in the sample are counted by the detector, resulting in a transmission spectrum. Because the resonance lines are extremely sharp (10^{-9} eV of the natural line width for ^{57}Fe in comparison with 14.4 keV of the emitted rays), the energy has to be modulated to obtain the resonance. The γ -rays energy can be modulated by a first-order Doppler effect, thus applying a relative motion to the source. For this reason the abscissa is expressed in millimeters per second; in ^{57}Fe a velocity of a few millimeters per second guarantees the resonance condition. The spectrum thus obtained consists of a series of absorption lines, the positions and intensities of which give the Mössbauer fingerprints of the studied material. In general, the total absorption

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intensity is a function also of the concentration of the Mössbauer nuclei, allowing semiquantitative analysis of the population in the different sites. Analysis of the absorption lines results in the hyperfine parameter, which quantifies the interactions between the nucleus and the environment. These parameters are: isomer shift, δ , quadrupole splitting, Δ (or ϵ when magnetic coupling is present), and magnetic splitting. Concerning magnetic splitting, only the contribution of internal magnetic field B , arising from the intrinsic magnetic property of the absorber, will be hereafter discussed.

Isomer shift, known also as the chemical isomer shift, is the result of a Coulomb interaction between the nucleus and the electronic charge density over its volume. It represents the difference in total electron density at the nucleus between the sample and standard, similar to the chemical shift in nuclear magnetic resonance (NMR) (see NUCLEAR MAGNETIC RESONANCE (NMR)). Therefore δ has to be expressed relative to a standard absorber; concerning ^{57}Fe , the standard is $\alpha\text{-Fe}$. In the spectrum δ is the displacement of the signal from the zero, as will be discussed below. In general, total electron density at the nucleus is affected by any variation in the number of electrons, or their distribution, in the valence shell. Therefore, with a certain nuclide in a specific matrix, a variation in δ reflects a change in the oxidation state. Furthermore, since the distribution of electrons on valence orbitals affects the electron density, δ is representative of high/low spin (hs/l_s) configurations. δ depends also on the relative change in nuclear radius between the excited and the ground state, which can be positive or negative, depending on whether the nucleus expands or contracts during decay to the ground state. In the case of ^{57}Fe there is an expansion in nuclear radius after the decay, that is, δ increases, decreasing the oxidation state. On the contrary, ^{119}Sn has a contraction in nuclear radius after decay, and thus δ decreases, decreasing the oxidation state.

Quadrupole splitting, Δ , describes the effect of the electric charge distribution on the nucleus (precisely the electric gradient field generated by the charge distribution on the nucleus). When a nonspherical charge distribution is present, the excited nuclear level loses its degeneracy, giving rise to a splitting in the lines, the so-called

doublet. The charge distribution is the sum of the lattice contribution (thus an external contribution with respect to the nucleus) and that due to bonding and/or nonbonding electrons, so variation in Δ reflects variation in the single contributions. With the exception of ionic systems, the contribution of the lattice is negligible in comparison with that resulting from bonding and/or nonbonding electrons, which mainly affect Δ . Variations in the charge distribution, for example due to a different site geometry and/or to various substituents and/or to a difference in the second coordination sphere, promote a variation in Δ . If the charge distribution is spherical, as when the site geometry is cubic and all the ligands are identical, the excited nuclear level preserves its degeneracy and the spectrum consists of a single line, a singlet, whose displacement from zero is δ . Conversely, when the charge distribution is nonspherical, as when the site geometry decreases in symmetry or when different ligands are coordinated to the same nucleus, the spectrum consists of a doublet. The center of gravity of the doublet corresponds to the δ , while the distance between the two minima corresponds to Δ . For instance, when two different structural sites are present, the spectrum shows two doublets characterized by different δ and Δ , whose intensities are representative of the population in the two sites. At the same time, a variation in Δ is observed when sites with the same geometry but chemically not equivalent are present. For instance, ^{57}Fe MS can easily discriminate Fe(III) from Fe(II), and the different coordination of both species, in clayey minerals. Fe(II) shows a δ higher than Fe(III), typically ≈ 1 mm/s instead of ≈ 0.35 mm/s.

The last hyperfine parameter originates from the magnetic dipole interaction between the nuclear magnetic moment and any magnetic fields acting on the nucleus. When a nucleus is placed in a magnetic field, the degeneracy of both ground and excited nuclear levels vanishes, resulting in magnetic splitting, and a multiplet (Zeeman splitting) is observed in the spectrum. With ^{57}Fe , the 3/2 excited level is split into four levels, while the 1/2 ground level is split into two, so six transitions are allowed, resulting in a sextet. The separation between line 1 and 6, the external lines, results in the intensity of B . B values are expressed in Tesla (T). As for δ and

Δ , B values quantify the local interactions at the nucleus, allowing a detailed description of the magnetic properties of the materials. With ^{57}Fe , the discrimination between hematite ($\alpha\text{-Fe}_2\text{O}_3$) and goethite ($\alpha\text{-FeOOH}$) can be on the basis of B . In both cases, Fe(III) occupies octahedral sites, but the former shows a B of approximately 51.7 T, while the latter shows a B of about 38 T. It is worthy to note that ^{57}Fe MS can support diffraction, especially when multiphase mixtures, containing tiny amounts of iron oxides, are analyzed. For instance, when studying pottery (see ELEMENTAL ANALYSIS OF POTTERY and POTTERY DATA QUANTIFICATION) MS can differentiate quite easily between magnetite and maghemite, two spinels whose formation depends on the firing atmosphere. These phases show similar X-ray diffraction (XRD) patterns, and the correct attribution could be tricky because of the large contribution of the other phases to the diffractogram. On the contrary, MS discriminates the two phases due to its sensitivity to local Fe interactions. Magnetite (Fe_3O_4) shows a spectrum with two distinct sextets, attributable to the tetrahedral and the octahedral Fe site in the structure. The two sextets differ for δ , Δ , and B values; tetrahedral ferric sites show the highest B , 49.2 T, and the lowest δ , 0.26 mm/s. The octahedral sites present parameters intermediate between Fe(III) and Fe(II) , indicating a charge transfer significantly faster than the Mössbauer time window (10^{-9} s). Conversely, maghemite ($\gamma\text{-Fe}_2\text{O}_3$) shows only a broad sextet, whose parameters are typical of Fe(III) in octahedral geometry (δ close to 0.36 mm/s and B close to 49 T).

For their intrinsic properties, hyperfine parameters are temperature dependent. In general, decreasing the measurement temperature below room temperature (usually at liquid nitrogen temperature) is normally preferred. First, the temperature decreasing increases the “rigidity” of the system, that is, it increases the number of recoilless events, improving the Mössbauer effect. Simultaneously, the different temperature dependence of the hyperfine parameters allows a better spectral resolution. Another relevant aspect of low-temperature experiments concerns the study of nanosized iron oxide. These species, due to magnetic properties connected to their small dimension, usually show a

doublet at room temperature and are indistinguishable from paramagnetic compounds. This phenomenon, known as superparamagnetism, is suppressed, lowering the measurement temperature. For instance, nanosized hematite (≈ 8 nm in diameter) shows a doublet at room temperature which transforms in a sextet at ≈ 77 K. On the other hand, microcrystalline hematite particles show a well-resolved sextet at room temperature.

Traditional experiments are performed in transmission mode; however, MS can be performed in backscattering mode, collecting conversion electrons (conversion electron Mössbauer spectroscopy (CEMS)), X-rays, and γ -rays that leave the absorber. Working in backscattering geometry allows noninvasive analysis on the “surface” of the sample. The investigated thickness changes from several hundreds of nanometers (≈ 200 nm) in CEMS to tens of microns by detecting X- and γ -rays.

The application of MS to archaeological materials allows an in-depth characterization of the material and it is particularly useful when the Mössbauer nucleus is used as a probe to understand the interaction of the material with the environment—that is, to study firing technology. It is successfully applied to investigate pottery, vitreous materials (see CONSERVATION OF VITREOUS MATERIALS and DETERIORATION OF VITREOUS MATERIALS), metallic artifacts, slag (see ORE AND SMELTING SLAG), pigments (see CHARACTERIZATION OF PIGMENTS), and inks (see INK). Almost all the literature is focused on investigation with ^{57}Fe ; there are few circumstances in which ^{119}Sn and ^{197}Au are used. Among the above-mentioned materials, clay-based ceramics are the most studied, thanks to the relatively high amount of Fe contained. Iron occurs in many silicates and oxides, and it changes easily its oxidation state as a result of environmental variations. It is therefore an ideal probe to understand pottery firing conditions. Since the pioneering works, MS has been used to estimate Fe(II) and Fe(III) content in pottery in order to understand the kiln's redox conditions. Moreover, it is used to link the Fe oxidation state to the pottery's color, especially when Fe(II) is present. In fact, grayish-dark hues can be related to the presence of Fe(II) -bearing minerals such as hercynite (Fe_2AlO_4) and/or to magnetite. Hercynite shows a doublet, whose

parameters are typical for Fe(II) in octahedral sites, while magnetite shows the magnetic pattern described above.

MS is particularly useful to follow the chemical and mineralogical transformation of iron-bearing minerals during experimental firing under controlled conditions. Literature data demonstrated that variations in Δ can be related to the chemico-physical transformation of the mineralogical assemblage during firing. It was observed that dehydroxylation of clay minerals, occurring between 400 and 600 °C, promotes a drastic increase in quadrupole splitting, while the formation of new phases, at higher temperature, involves a decrease of Δ values (Wagner and Kyek 2004). The information obtained by MS can be used as support to evaluate the firing temperature. To understand the nucleation and growth processes of iron oxides in pottery and to relate them to pottery coloration, low-temperature measurements are necessary. For instance, a coloring mechanism involved during the firing of carbonate-rich clays was proposed by Nodari et al. (2007). Comparing the data obtained at room temperature, representative of microcrystalline hematite, with those obtained at 80 K, representative of both macro- and nanocrystalline hematite, the authors explained the pale colorations of high fired calcareous pottery. It was shown that at temperatures higher than 900 °C, the 80K magnetic pattern increases in relative area, indicating an increment in nanosized hematite versus coarser-grained hematite particles. The presence of nanosized hematite, dispersed in a Ca-rich amorphous phase, affects the pottery's color. In fact, at the same firing temperature, Ca-rich findings usually show a creamy or brownish hue, contrary to the intense red/orange color shown by carbonate-free pottery.

The redox condition in glass (see GLASS AND FAIENCE and GLASS COLOR) manufacturing can be studied by MS. Since iron is almost regularly present in ancient glasses, as a result of impurities or intentionally added as colorant, it can be used as a probe for determining the redox conditions in the glassy matrix. This is particularly true when iron is the only chromophore. In such conditions it is possible to associate the color with the Fe(II)/Fe(III) ratio, that is, with the redox condition of the furnace.

Analyzing ancient mixed-alkali vitreous findings, it was observed that oxidizing conditions, with an Fe(II)/Fe(III) < 0.5, promote a dark-yellow coloration. The hue is attributable to octahedral and tetrahedral Fe(III) sites rather than the presence of nanosized ferric oxides. In nonoxidizing conditions, with an Fe(II)/Fe(III) > 3.0, a blue color is obtained, as a result of the presence of a large amount of Fe(II) in octahedral sites (Artioli et al. 2009). Between these Fe(II)/Fe(III) ratios, glasses show a green-bluish coloration, and Fe is distributed over octahedral and tetrahedral sites. It is interesting to point out that some findings with an unusually high amount of Fe(II) show an amber coloration. Atomic absorption analyses show the presence of Fe only as chromophore, together with a non-negligible amount of sulfur. MS reveals the presence of a significant amount of Fe(II) ($\approx$ 80% in relative area), whose parameters are distinctive for Fe(II) in 1s configuration (Bianchin et al. 2005). This suggests the presence of Fe-S adducts, which impart the typical amber hue.

In order to understand the nature of Au nanoparticles in eighteenth-century ruby glasses and the role of Sn in Au nanoparticle formation, a series of ^{197}Au and ^{119}Sn Mössbauer experiments were performed on mock-up samples by Wagner et al. (2000) and Haslbeck et al. (2005). The samples were prepared by adding to soda-lime glass and/or sodium silicate glass various amounts of Au and Sn, as KAu(CN)_2 and/or HAuCl_4 and SnO_2 , respectively. The raw materials were melted at 1,400 °C, quenched, and, at a later time, annealed between 500 and 700 °C. After the annealing procedure the ruby color strikes, as a result of the formation of Au nanoparticles. The presence of Au(I) and Sn(IV) and Sn(II) was observed in the quenched colorless glass, while Au(0) and Sn(IV) were detected in the annealed glass. It was observed that only the presence of Sn in raw materials promotes the formation of a large fraction of small Au nanoparticles enhancing the ruby color. On the basis of Mössbauer data, the role of Sn(II) as a reducing agent was proposed: The formation of Sn(II) during melting promotes the reduction of Au(I) to Au(0), and the subsequent formation of gold cluster during annealing.

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Nanoarchaeology

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To know what a nanomaterial is has been one of the most discussed questions in recent years. In fact, in 2011 the European Commission published a recommendation (2011/696/EU) to propose a nanomaterial definition to determine when a material should be considered a nanomaterial for regulatory purposes in the European Union. Currently, the EU recommends the following definition of the term: “*Nanomaterial*” means a natural, incidental or manufactured material containing particles, in an unbound state or as an aggregate or as an agglomerate and where, for 50% or more of the particles in the number size distribution, one or more external dimensions is in the size range 1 nm–100 nm. This definition is based exclusively on the size of the constituent particles of a material, where “particle” means a minute piece of matter with defined physical boundaries. This is an example of the complexity of the subject, and other international standardization organizations are in constant discussion and revision of the term.

In this current frame, advances in the use of very sophisticated analytical techniques have collaborated to understanding the structure and composition of many ancient materials, and the results have demonstrated the surprising presence of nanomaterials in these early objects, thus explaining many of their properties. “Intentionally manufactured” or not, just as the new nanomaterials, these products have been present since antiquity with similar features to those currently created.

Nanoparticles in vitreous materials (glass and glazes)

The most frequently described object where nanoparticles are present in its structure is the

famous Lycurgus Cup (see GLASS AND FAIENCE and GLAZES, SLIPS, AND PAINTS). It is one of the most technically sophisticated glass objects made before the modern era. Historically it belongs to a type of Roman vessel called “cage cups” and is generally dated to the fourth century CE. The object is especially known for the unusual optical properties of its glass, the so-called dichroic effect: The glass looks like jade with an opaque greenish-yellow tone in direct light, but it turns to a translucent ruby color in transmitted light. Although the cup came to scholarly attention quite early, it was in the late 1980s when the examination of a small fragment by transmission electron microscopy (see TEM AND ARCHAEOLOGICAL MATERIALS) (TEM) demonstrated the presence of minute particles of metal (50–100 nm in diameter)—a silver-gold alloy with a ratio of about 7:3 (containing also about 10% copper) inside the glass matrix and responsible for the dichroic effect (Barber and Freestone 1990).

In fact, it is well known that the presence of small particles of metallic gold is responsible for the red-ruby color of glass. The art of producing gold ruby glasses goes far back in time, at least to the Roman period. Some researchers suggest it dates back to the seventh century BCE, where Assyrian clay tablets (see CLAY TABLETS) mention a recipe allowing the production of “an artificial coral.” The red-ruby pigment was cited as early as the ninth century by Islamic scholars. In 1546, Agricola talked in his *De Natura Fossilium* about how Venetian glassmakers used gold to tint the glass ruby red. In the seventeenth century, gold ruby glass manufacture seems to have developed, when “Purple of Cassius” (a colloidal suspension of gold obtained by reducing a gold (III) chloride aqueous solution with stannous chloride) was added to the glass batch compositions.

Still more ancient glass technologies already exploited the presence of metal particles in the glass matrix to produce red color. As early as 1500 BCE, copper red glass was manufactured in Egypt. In Europe, red glass colored by copper dates from the late Bronze Age (1200–1000 BCE) in Italy. “Hematinum” red glass was first described

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by the Roman historian Pliny the Elder; it is an opaque glass colored by particles of a size with the same order of magnitude as the wavelength. The origin of the color in copper red glasses has been debated, with some authors stating that it is due to metallic copper (Cu) nanoparticles, while others state that it is due to Cu_2O nanoparticles or to both. Electron microscopy observations have demonstrated that the copper particles are less than $0.5\ \mu\text{m}$ across.

Another element used to color glass because of its potential nanodimensions was silver. The decoration of glass using silver pigments appeared in the early Islamic world (eighth century CE) and they were later introduced in the preparation of European medieval glasses. In the silver stained glass, the yellow coloration is the result of the formation of silver nanoclusters. During the glass manufacture, metallic silver aggregates and it forms spherical crystals with a diameter between 1 and 100 nm. Depending on the size, shape, and particle size distribution, these nanoparticles affect the final color of silver stain.

Actually, these metallic nanoparticles were used worldwide. For instance, we can also find glasses colored by copper in Satsuma Japanese objects (nineteenth century, Edo period) and in ancient Thai decorations. Even this type of metallic pigment was not limited to glass manufacture and they were also introduced to produce colored glazes on ceramics in ancient times. The secret of the Chinese blood-red “Sang de Boeuf” or Lang yao hong pottery (eighteenth century, Qing dynasty) was the presence of copper in the glaze, and a similar technique gave rise to the red “flambé” and mixed blue-red Jun glazed porcelains from the middle-aged Song and Ming to Qing Chinese dynasties, as well as some Vietnamese porcelains and stonewares. Moreover, the use of gold in a similar recipe to the “Purple of Cassius” was present in China in the manufacture of the “Famille Rose” porcelain (eighteenth century) and in the French workshops of Sèvres to produce gold-based purple colorants, like in “Rose Pompadour” glazing.

However, one of the most investigated glaze decorations based on the presence of metallic nanoparticles is luster (Figure 1). It is a type of ceramic decoration, which results in a beautiful metallic shine and colored (golden, yellow, red) iridescences on the surface of the ceramic object.

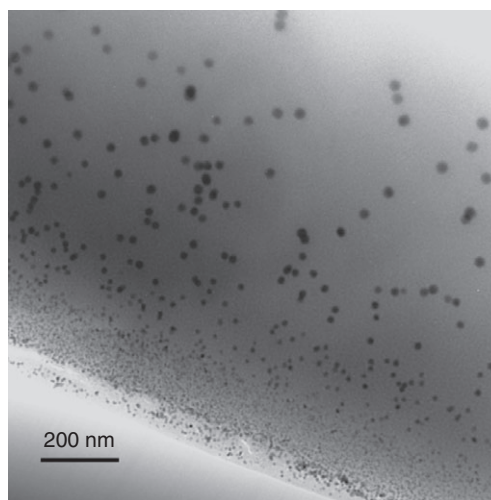


Figure 1 Transmission electron microscopy (TEM) image of metallic silver nanoparticles embedded in a glaze producing a golden luster decoration (Syrian luster ware).

Source: Reproduced with permission from Pérez-Arantequi et al. 2004.

The earliest luster was probably made in Iraq in the early ninth century CE on tin-glazed ceramics, but the technology spread from the Middle East to Persia, Egypt, Spain, and Italy. Analytical electron microscopy revealed that luster ceramic decoration was the first manufactured nanostructured metallic thin film (Pérez-Arantequi and Larrea 2003). It is formed by a homogeneous surface microstructure composed by small quasi-spherical clusters embedded in the glaze, with a usual total thickness of 200–500 nm of this structure, in any case, less than $1\ \mu\text{m}$. The clusters are metallic copper and/or silver nanoparticles, with diverse diameters (less than 50 nm), and sometimes arranged according to different sizes from the outer to the inner layers.

Additionally to these elements, in ancient Jian wares (Song dynasty, 960–1279 CE), famous for their lustrous black glaze that exhibits unique colored patterns, a scientific study (Dejoie et al. 2014) identified iron oxide crystallites in the brownish-colored “Hare’s Fur” strips: a mixture of $\alpha\text{-Fe}_2\text{O}_3$ (hematite) and the metastable $\varepsilon\text{-Fe}_2\text{O}_3$ phases. The $\varepsilon\text{-Fe}_2\text{O}_3$ there consisted of randomly oriented sub-100-nm-size crystals dispersed within the glaze below the surface.

Nanomaterials in pigments

Maya blue was first produced by the Mayas in Mesoamerica about the eighth century CE, and extended well into the colonial era as late as the twentieth century, widely used in mural paintings, ceramics, and codices. The pigment is extremely stable and it has a bright turquoise hue; its remarkable properties have attracted the efforts of many researchers to explain and justify Maya blue features over decades. Since the publication of the paper by José-Yacamán et al. (1996), Maya blue can be also considered among the ancient nanostructured materials. The pigment belongs to this material category because of its structure and composition, combining palygorskite (a clay) and indigo (an organic dye). Using TEM, the painting samples showed regions containing well-shaped crystals of palygorskite, but with a superlattice and then a period of about 14 nm, explained because impurities (indigo molecules) are stacked inside the pillared structure of the clay. However, there were also other regions in the samples with a substrate of amorphous SiO_2 that contained metal nanoparticles, most of them identified as Fe and Cr, but also Mn, Ti, and V, sometimes in a metallic state and others as oxides (i.e., $\alpha\text{-Fe}_2\text{O}_3$), and probably with strong interactions between the nanoparticles and the SiO_2 substrate. The presence of these metallic impurities and their oxidation or encapsulation, together with the indigo molecules encapsulated in the clay pores, would be among the reasons for the acid-resistant property of the pigment and its color. Later studies justified the formation of Maya blue on the basis of the indigo adsorption only in the “grooves” of the palygorskite, instead of inside their channels (Chiari et al. 2008). Besides, palygorskite structure itself has dimensions close to nanomaterials (the fibers have a diameter range from 140 to 200 nm and length from 1.2 to 2.8 μm).

As well as nanostructured Maya blue, at present, other ancient pigments like Egyptian blue (formed by calcium copper tetrasilicate ($\text{CaCuSi}_4\text{O}_{10}$), quartz, and amorphous silica (SiO_2)) are being considered because of their possible nanodimensions. The facile exfoliation of bulk $\text{CaCuSi}_4\text{O}_{10}$ into nanosheets (two-dimensional nanomaterial) and the strong

near-infrared (IR) emission preserved in these exfoliated samples made this pigment very promising in modern technochemical applications (Johnson-McDaniel et al. 2013). Similar behavior could be expected from Han blue, a barium copper tetrasilicate ($\text{BaCuSi}_4\text{O}_{10}$).

Other nanomaterials in ancient objects

In metals, the comparison of the structure of seventeenth-century Damascene steel blades showed a common feature, responsible for their extraordinary mechanical properties. In spite of the different microstructures, colonies of wire- and tube-like particles with diameters of 40–50 nm were observed by high-resolution TEM (see TRANSMISSION ELECTRON MICROSCOPY); the main phase forming these particles was crystalline cementite (Fe_3C), covered by carbon nanotubes (Reibold et al. 2006).

Another study by TEM evidenced a nanocrystalline structure in an ancient metal mirror alloy, a Cu-32 wt% Sn alloy that had been made by an age-old crafted casting process. Within the dendritic regions, a preponderance of quasi-crystalline nanoparticles, typically with size less than 10 nm, was observed (Sekhar et al. 2015). Bronze mirrors of high tin composition have been manufactured for around 4,000 years and probably the earliest use was in China.

A completely different illustration of ancient nanomaterial is that used to dye hair black since the Greco-Roman period. As a consequence of the chemical treatment, synthesized galena (lead sulfide) nanocrystals with a size of about 5 nm precipitate inside the hair to blacken it (Walter et al. 2006).

Besides all these manufactured products, natural and nonintentional nanomaterials have been also used since antiquity. For instance, asbestos is a group of naturally occurring mineral nanofibers (~ 10 nm in diameter) that represent the most multifunctional nanomaterial in history, with many products and applications since about 1000 BCE because of its range of useful properties. Clay minerals are good examples of the use of natural nanomaterials since ancient times, for medicinal and cosmetic treatments, bleaching of wool and clothes, and so on. Carbonaceous combustion

soot and black carbon are among the ancient and persistent nanoparticulates, used as pigment or as a component of inks. TEM analysis revealed that “Kaajal” (the traditional Indian black cosmetic) contained carbon nanoparticles of different sizes ranging from 2–3 nm and 35–45 nm (Mandal et al. 2013). Silver (in colloidal form) was used as a water disinfectant in classic Greece because of its antibacterial and antifungal properties.

SEE ALSO: Characterization of Ceramics;
Characterization of Metals and Alloys;
Characterization of Pigments; Glass Color

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Neutron Activation Analysis (NAA)

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Neutron activation analysis (NAA) is a non-destructive, multi-element nuclear analytical technique with excellent sensitivity, great accuracy, and precision that has been successfully used in archaeological and heritage studies since the 1960s (Speakman and Glascock 2007). NAA is based on the detection of the radiation emitted from materials that have previously been irradiated with neutrons. The nuclear reactions carried out in the sample material lead to production of radio-isotopes that emit characteristic gamma-rays (see ISOTOPES; NEUTRON RESONANCE ANALYSIS (NRA); and NON-STABLE ISOTOPES IN ARCHAEOLOGY). The analysis of the acquired gamma-ray energy spectra enables the qualitative and quantitative determination of the elemental composition of the sample under investigation. In order to identify—through the radioactive nuclei produced—the corresponding target nuclei and, hence, the elements composing the sample material, detailed knowledge of the occurring nuclear reactions and reaction rates is required. An important parameter in the activation process is the energy spectrum of the neutrons incident on the sample, which determines the type of nuclear reaction as well as the probability of its realization, and consequently defines the resulting radioactive products. Absolute, comparative, internal monostandard, and k_0 techniques have been developed to quantify the elemental analysis results (Greenberg, Bode, and De Nadai Fernandes 2011).

A nuclear reaction which is often used in NAA is the neutron capture (n, γ) reaction followed by emission of gamma-rays. The interaction of neutron with the target nucleus results in its capture and the production of a compound excited

nucleus. During the decay of the compound nucleus one or more characteristic gamma-rays, known as "prompt" gamma-rays, are emitted. The decay of the compound nucleus may lead to the formation of a radioactive nucleus which thereafter decays, also emitting characteristic gamma-rays. These gamma-rays are called "delayed" so as to be distinguished from the "prompt" gamma-rays. Depending on the type of gamma-rays detected, NAA is classified either as prompt gamma-ray neutron activation analysis (PGNAA), in which sample irradiation and measurements are performed simultaneously, or delayed gamma-ray neutron activation analysis (DGNAA), where gamma-ray measurements start after the end of irradiation. A method for optimization of the detection limit of specific elements (usually forming short-lived radionuclides) is the irradiation and measurement of a sample repeatedly for a short period of time and summation of the gamma-ray spectra from individual runs. This technique is called cyclic neutron activation analysis (CNAA). The need for sample preparation or special treatment during the analysis procedure is another criterion used to assort NAA. According to this classification, the technique is termed instrumental neutron activation analysis (INAA) when no sample treatment is involved and radiochemical neutron activation analysis (RNAA) when the irradiated sample is subjected to chemical separation in order to remove interfering species or to concentrate the radioisotope of interest.

NAA experiments have been performed utilizing thermal, epithermal, and fast neutrons obtained from all available types of neutron sources (nuclear reactors, accelerators, isotopic sources). Nevertheless, the optimum measurement sensitivity is achieved in fission reactors due to the significantly higher neutron fluence rates produced in these facilities.

NAA has important features outbalancing other analytical techniques. First, it is versatile and can be applied on solids, liquids, suspensions, slurries, and gases. It requires almost no sample preparation, eliminating the possibility of

sample contamination in the laboratory, while it is nondestructive, allowing reusing the sample in several experiments. Moreover, it is a time-saving technique enabling the simultaneous determination of several (major, minor, and trace) elements in the same sample. Since the half-lives of different radioisotopes differ, measurement can be delayed to allow interfering species to decay and, thus, eliminate interferences and achieve lower detection limits. NAA provides excellent sensitivity, great accuracy, and precision. Depending on the material under investigation, the sensitivity of the technique may be of the order of parts per billion (ppb). According to Pollard and Heron (1996), accuracy of NAA is in the region of 5 percent and relative precision is often better than 0.1 percent. It has great linearity, which can reach up to 12 orders of magnitude for certain elements; hence, a wide range of elements and concentrations can be detected at the same time. Furthermore, it can be widely applied, since approximately 70 percent of the elements of the periodic table have properties that allow their detection using NAA; namely they are stable isotopes that can be activated if irradiated with neutrons. Because of its great advantages, NAA has been established as an important analytical tool for chemical characterization studies and is often considered to be the reference technique as compared to other analytical methods. The simplicity of the procedure, the fact that little or no sample consumption occurs during the analytical process, and its excellent sensitivity are great benefits that distinguish NAA from similar techniques.

NAA has found a broad range of applications in several fields of science and technology, including archaeology, archaeometry, and heritage studies. Since the 1960s, NAA has been used to analyze archaeological findings or verify the authenticity of important historical objects, distinguishing fraudulent from real artifacts. Moreover, NAA is commonly recognized as the method of choice for archaeological provenance investigations (Speakman and Glascock 2007). Within the context of such studies, the elemental composition profile derived by the analysis of the “unknown” archaeological object is compared against known profiles of already identified raw materials, aiming to find a correlation that will

indicate its exact place of origin. Among the successful applications of the technique one can find chemical characterizations of potsherds, obsidian implements (see *CHERT, SILEX, AND OBSIDIAN SOURCING*), silver and gold coins, glass (see *GLASS AND FAIENCE*), metals (see *CHARACTERIZATION OF METALS AND ALLOYS*), and pigments from paintings and other valuable artworks (see *CHARACTERIZATION OF PIGMENTS*).

In conventional NAA, however, the mass of analyzed samples is in the range of milligrams to grams (or of a few microliters to milliliters in volume), representing only a small portion of the bulk material. This limitation proves to be an important issue that inevitably restricts the potential of the technique. In authenticity and provenance studies, for example, the analyzed archaeological objects are usually precious, non-replaceable artifacts that need to be preserved intact and cannot be damaged for sampling purposes. Furthermore, in the case of heterogeneous materials, which are often met in archaeological and heritage studies, representative sampling is usually a very difficult or even impossible task. In order to fulfill the demand for a nondestructive method capable of analyzing larger material volumes and whole objects, the method of large sample neutron activation analysis (LSNAA) was developed.

In LSNAA, the nondestructive, multi-element character of the conventional NAA technique is combined with the ability to analyze bulk objects, up to several liters in volume, as a whole. Based on the fact that the mean free path of neutrons and gamma-rays within materials is in the order of several centimeters, that is, neutrons and gamma-rays can penetrate deeply into bulk objects, LSNAA enables the nondestructive analysis of voluminous samples, overcoming the obstacle of limited analyzed mass.

The basic principles of LSNAA are the same as those of NAA. The large sample is irradiated in a neutron field and is subsequently transferred to a suitable gamma-ray spectrometry facility to be counted either as a whole or using segmented scanning. The gamma-rays emitted from the activated material are identified and the activity induced in the sample volume is quantified. Finally, the spectra analysis results are interpreted in terms of elemental concentrations. The only parameter that strongly differentiates LSNAA

from the “traditional” technique is the large volume of the studied sample. To account for the voluminous character, a number of corrections need to be applied to the experimental data. These corrections are mainly related to the interaction of neutrons and photons within the sample material, as well as the inhomogeneity and asymmetry of the bulk object. In particular, corrections are required for neutron self-shielding during sample irradiation, gamma-ray self-attenuation during gamma-counting, volume distribution of activity within the large sample material, irregular sample shape, and material inhomogeneity effects. Different methods and algorithms have been proposed for the correction and quantification of LSNA results (Bode 2008).

The development of LSNA increased the potential of the activation analysis method, unfolding new possibilities. As in NAA, the feature of multi-element compositional analysis is coupled with the excellent sensitivity, great accuracy, and precision achieved. In addition, neither chemical nor any other sample preparation is needed. In LSNA, however, the advantages of the conventional technique are significantly extended due to the unique capability of nondestructive bulk material analysis. Since whole-object analysis is performed and no subsampling is required, precious artifacts and historical pieces can be studied without any concerns about their integrity. Apart from the obvious value of preserving the integrity of a precious archaeological finding, the measurement procedure can be repeated whenever it is needed. Moreover, it minimizes—if not totally obliterates—the risks of contamination (e.g., due to drill-bit) during the sampling procedure. Besides, the elimination of the need for subsampling is extremely important in the case of inhomogeneous materials, which cannot be cut into pieces, grinded, pulverized, or in any other way homogenized in order to be analyzed. Another important aspect is that LSNA can be applied using facilities with relatively low neutron fluxes (in the order of 10^6 – 10^9 cm⁻² s⁻¹). Given the fact that the “loss” in the neutron flux is compensated by the greater mass of the analyzed material, low neutron fluxes are adequate for analysis, so a wide range of neutron sources can be used for LSNA experiments: small and medium power reactors, reactor thermal neutron

columns, as well as isotopic neutron sources and neutron generators. At the same time, irradiation in a neutron field with fluxes lower than those used in the conventional small sample analysis (i.e., of the order of 10^7 cm⁻² s⁻¹ for LSNA instead of 10^{13} cm⁻² s⁻¹ for NAA, respectively) implies lower residual specific activity induced in the studied sample. Therefore, shortly after the completion of the irradiation, the sample can be released from regulatory control without any further concerns on the activity levels. In the case of pottery samples, in particular, their low activation properties as compared to other materials (e.g., metals) make the technique ideal for characterization of ceramics (see CHARACTERIZATION OF CERAMICS).

Several analytical techniques have been used in archaeological and heritage research. X-ray fluorescence (XRF) (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), particle-induced X-ray emission (PIXE) (see ION BEAM ANALYSIS (PIXE/RBS)), atomic absorption spectroscopy (AAS), ion beam analysis (IBA), inductively coupled plasma spectroscopy (ICP) (see ICP-MS AND MATERIAL ANALYSIS), scanning electron microscopy (SEM), radiocarbon dating (see RADIOCARBON CALIBRATION AND AGE ESTIMATION), thermoluminescence (see THERMOLUMINESCENCE), and optical methods (see OPTICAL MICROSCOPY) have been applied, among others, for provenance studies, authenticity verification, dating, and restoration of artifacts. Of course, not all techniques are applicable in each sample case. The selection of the appropriate method depends on the type of the studied material as well as on the objective of the analysis. For example, if the aim of the study is to trace a pottery artifact to its source, namely to determine its elemental fingerprint, then a technique able to provide information on trace elements (such as XRF or NAA) should be employed. Nevertheless, due to its various advantages and, in particular, due to its ability to analyze whole objects, LSNA has proven to be a unique analytical tool, which seems to outweigh other established nondestructive methods, at least in certain cases and applications. For instance, techniques such as IBA, XRF, and PIXE can only analyze superficial layers of the sample material and thus provide limited information on its elemental composition in depth. So, they cannot be used for the analysis

of voluminous or inhomogeneous materials, where the surface profiling is not sufficient. In addition, LSNA results are not affected by post-depositional elemental alterations caused on the sample surface due to, for example, oxidation or sediment deposition, since the analytical information is provided from the total volume of the bulk material and not only from its surface layers. This is a significant aspect, especially in cases of archaeological findings that have been either buried in the earth or sunken in the ocean for a prolonged period, resulting in erosion or distortion of their surface (Schwedt, Mommsen, and Zacharias 2004).

Recognizing the great potential of the technique in the fields of archaeology and heritage studies, archaeologists, art historians, conservators, and museum curators have used LSNA in diverse material investigations. The technique has been successfully applied for the analysis of stone samples, entire potsherds of archaeological interest, irregular-shaped bulk historical objects, and artifacts (Dasari et al. 2010; Bedregal et al. 2014; Vasilopoulou et al. 2015). It has been also used in provenance studies of traditional pottery and in authentication studies of ancient porcelain ware (Zhu et al. 2013).

Further efforts and studies could include—without being limited to—the development of LSNA facilities based on isotopic neutron sources (e.g., ^{252}Cf , Am-Be) or neutron generators, allowing the application of the technique even in cases where a nuclear reactor is not readily available. Such an approach would also facilitate the implementation of in-situ analyses of voluminous objects that cannot be transferred to the laboratory, such as pillars, murals, frescoes, mosaics, and other parts of historical buildings or archaeological sites. Portable LSNA would be a valuable field tool for the in-depth study of various materials, complementing the information that portable X-ray fluorescence spectroscopy (pXRF) (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)) provides. Another aspect that is worth being investigated is the use of NAA as a screening method for inhomogeneous bulk materials and objects. For instance, the development of neutron imaging and tomography is of great importance in authentication and conservation studies (see NEUTRON IMAGING AND TOMOGRAPHY IN CONSERVATION).

The combination of computed tomography or neutron radiography techniques (see NEUTRON RADIOGRAPHY AND TOMOGRAPHY) with focused neutron beams and prompt gamma-ray analysis may lead to new and innovative applications.

SEE ALSO: Compositional Data Analysis; Elemental Analysis of Pottery; INAA and Material Analysis; Nondestructive Compositional Analysis of Ceramics

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Neutron Diffraction (ND)

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Neutron diffraction can determine the bulk microstructure of archaeological materials by completely noninvasive means, in terms of the mineral and metallic constituents. Neutron diffraction is consistent with the ethical considerations of conservation science (see CONSERVATION SCIENCE). Assemblages of intact artifacts can be analyzed with no need to remove samples; the object is unaltered by the neutron beam, and no special sample preparation or environment is required. A far greater number of objects can be analyzed than would ever be possible by metallographic techniques (see METALLOGRAPHY), as curators rarely allow destructive sampling for optical microscopy. The aim of the crystallographic characterization is to reconstruct technical details of fabrication methods in early metalworking, such as alloying, casting, hammering, and heat-treatment. The main advantage of neutron diffraction compared to X-ray diffraction in archaeometallurgy is the high penetration property of a neutron beam. The method measures right through the thickness of an object, giving average quantitative structure data from internal parts (Kockelmann, Kirfel, and Haehnel 2001; Kockelmann et al. 2006). Emerging Bragg-edge transmission analysis techniques provide new opportunities for structure studies of archaeological materials in a radiography-type setup. Neutron diffraction analyses are performed at “large-scale” facilities such as nuclear reactor sources and accelerator-based neutron spallation sources.

The information from neutron diffraction is used in conjunction with other nondestructive methods. X-ray radiography (see X-RAY RADIOGRAPHY), neutron radiography (see NEUTRON

RADIOGRAPHY AND TOMOGRAPHY), and X-ray tomography (see X-RAY TOMOGRAPHY) are used to assess the preservation state of an object and to help find the analysis points for neutron diffraction. Neutron diffraction can also be useful in selecting points for metallographic sampling if, for example, a large assemblage of objects is being examined, but destructive sampling can only be carried out on a very limited proportion. Spatially resolved elemental data can be acquired from objects using complementary noninvasive neutron-based techniques such as prompt gamma activation analysis and neutron resonance capture analysis (see NEUTRON RESONANCE ANALYSIS (NRA)). Multiple data points can be collected by neutron diffraction, overcoming the interpretive problem of relying on just one or two very small metallography sections in order to characterize a whole—typically heterogeneous—ancient artifact.

High-intensity beams of thermal and cold neutrons are produced in nuclear reactions, in either nuclear reactors or accelerator-based spallation neutron sources. Neutrons have no charge, are able to penetrate deep into a material, and hence come close to nuclei unimpeded by the electrical Coulomb forces, and interact with the nuclei via the strong force. The interactions are weak, and thus, when neutrons hit a solid, most of them pass through it and only a small fraction is scattered. Neutrons are therefore able to penetrate bulky or thick samples that can be several centimeters in diameter. Neutrons have a spin and magnetic moment, and hence interact with unpaired magnetic moments of the electron shells of atoms.

Neutron diffraction is a phase- and structure-sensitive method. Diffraction (see DIFFRACTION) is described by Bragg's law which treats the scattering process as reflection by crystal planes. The primary difference between X-ray and neutron diffraction lies in the form factor, which for neutrons is termed “scattering length” and describes the interaction between neutron and nucleus. For most isotopes the scattering length adopts a fixed value, that is, it does not depend on the energy

and scattering angle of the diffracted neutrons, in contrast to the form factor for X-ray diffraction. The neutron scattering length varies in an almost random manner with atomic number in the periodic table of elements. By comparison, for X-rays the atomic form factor is related to the number of electrons in orbitals surrounding the nucleus. Consequently, in the presence of heavy atoms, light atoms such as hydrogen and oxygen have small scattering powers for X-rays, but have good visibility in neutron scattering. The magnetic interaction of neutrons with long-range ordered structures of magnetic moments gives rise to magnetic diffraction peaks which can be used to identify and study ferromagnetic, ferrimagnetic, and antiferromagnetic structures of, for instance, ferritic iron, magnetite, and hematite.

The common neutron diffraction methods in archaeological science are derived from well-known X-ray or neutron powder diffraction approaches. Polycrystalline archaeological materials will contain one or more crystalline phases, with distinct crystal structures and compositions according to their locations in phase diagrams. As with other diffraction methods,

neutron diffraction can disentangle, quantify, and characterize phases in polycrystalline mixtures if present in sufficient amounts. Neutrons penetrate inorganic objects better than X-rays, for instance, allowing measurement of thick lead or leaded-bronze objects. Neutron analysis can determine how much metal is preserved under thick corrosion layers. The bulk composition and the microstructure of the metal is determined independent of the corrosion phases, as these are detected as distinct signals.

Neutron diffraction does not require material to be removed from the object. The method uses a large beam that illuminates the whole object, or part of the object. The incident neutron beam is collimated to cross-sections of a few square millimeters or centimeters, in analogy with what is routinely carried out to measure residual strains via neutron diffraction (Figure 1a). The sample or an entire object is usually placed in air on a remote-controllable laboratory table without any sample preparation. Sample positioning tables on neutron diffractometers may accommodate 1-m-large objects. The part of the object to be studied is aligned in the neutron beam

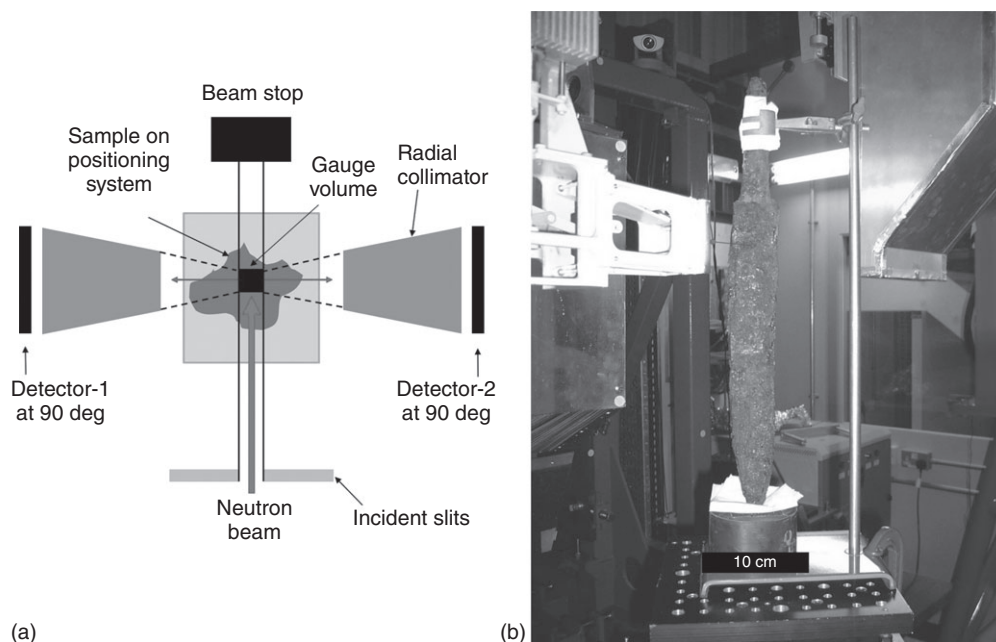


Figure 1 Analytical setup for neutron diffraction. (a) Schematic of a diffractometer at a pulsed neutron source with diffraction detectors at 90 degrees. (b) An Early Medieval iron sword mounted for neutron analysis by the conservation scientist.

(Figure 1b). Analysis points are selected based on visual features on the surface of the object, on X-ray radiographies, neutron radiographies or tomographies, or 3D laser scans of the external surface. Neutrons penetrate into the interior of the object; most neutrons pass through without interaction and are collected in a neutron camera or are removed by a “beamstop.” Part of the neutron beam is scattered in the sample, and part of those neutrons are registered in neutron diffraction detectors that are typically at a distance of 1–2 m from the sample. By collimating both the incident and diffracted beams, only neutrons are recorded that enter and emanate from a certain “gauge volume” inside the sample (Figure 1a). The minimum gauge volume for neutron diffraction is in the order of 1 mm³. By scanning the laboratory table, different parts of the sample can be interrogated and point-by-point structure maps can be obtained. It takes typically a few minutes up to several hours to collect a data point, depending on the neutron source strength, the gauge volume size, the detection efficiency, and the interaction cross-sections of the material. Multiple points can be collected across an object to produce a linear scan, or a 2D or 3D structure map.

The angle-dispersive neutron diffractometer uses a monochromatic beam, analogous to the Debye-Scherrer geometry in X-ray diffraction; diffracted neutrons are registered as a function of the scattering angle. The energy-dispersive neutron diffractometer uses a polychromatic beam, and diffracted neutrons are registered as a function of neutron energy or neutron wavelength. In either case, diffraction patterns are often displayed as counts versus crystallographic d-spacing (Figure 2) by making use of Bragg’s law.

Neutron diffraction at a pulsed spallation source has many advantages, such as ease of sample positioning and short data collection times. Data are collected in a combined angle- and energy-dispersive mode with time-resolving detectors at given scattering angles. Energy-discrimination is straightforwardly achieved by time-of-flight (ToF) measurements. With a given flight path and measured arrival time of a neutron in the detector, the velocity of the neutron and, via deBroglie’s relation, the wavelength can be determined. The sample is irradiated with polychromatic bunches of

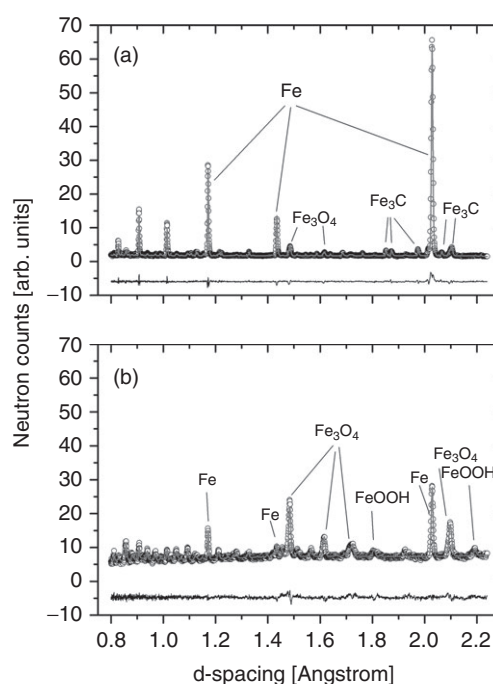


Figure 2 Neutron diffraction patterns from 2×2×2 mm² volumes of an Early Medieval iron sword. Some of the strong Bragg peaks are labeled. (a) Rietveld analyzed pattern from the back of the sword of internal volume underneath the corrosion layers, exhibiting ferrite, cementite, and magnetite. (b) Diffraction pattern from the edge of the sword, exhibiting magnetite and goethite phases in addition to ferrite.

neutrons which are registered in multidetector arrays comprised of hundreds and thousands of individual elements, each of them yielding a ToF diffraction pattern. This is a particularly useful feature for archaeological studies where a detector at a convenient scattering angle can be chosen. This also means that the data collection can be performed on stationary objects, or with minimal sample movements. The patterns from different detector elements are normally summed up to increase counting statistics and to simplify the data analysis. For certain applications, as is the case for texture studies, the diffraction patterns from different detectors are analyzed separately.

An important parameter of a neutron diffractometer is its resolution, describing the instrumental contribution to the Bragg peak widths. It depends on, among other things, the

chosen wavelength and the scattering angle. On a neutron diffractometer, the best resolution is achieved at high scattering angles, yielding the sharpest diffraction peaks, where sample-related peak broadening effects are recognized first. A good instrument resolution is required for peak separation in multi-phase sample patterns, for line-width analyses, and for accurate determination of lattice parameters.

A neutron diffraction pattern contains a series of Bragg reflections. The positions, widths, and intensities of Bragg peaks of a phase are analyzed, much like X-ray diffraction patterns, in terms of unit cell dimensions, crystal structure, microstructure, and preferred orientation of crystallites. Quantitative analysis can be performed by Rietveld refinement (Figure 2). The Rietveld profile refinement technique (Rietveld 1969) is an established method for quantitative phase and structure analysis in X-ray and neutron powder diffractometry. Rietveld analysis is performed by least-squares fitting calculated diffraction patterns against observed diffraction patterns, as shown in Figure 2, based on a structure model made up of the different phases in the sample. A full-pattern and multi-pattern Rietveld fitting approach is used to quantify the phase compositions, structure parameters, microstructure parameters, and crystallographic texture. The appeal of Rietveld methods for analysis of archaeological materials lies in its robustness with neutron data. Also, no internal standard is required for evaluation of relative phase fractions.

Neutron diffraction provides a structural characterization of crystalline phases, allowing description of metallurgical manufacturing techniques and evaluation of the state of preservation. Each corrosion compound forms a separate mineral phase, which can be distinguished and quantified from the diffraction pattern. The volume of preserved metal that is present underneath the corrosion layers can be calculated. Neutron diffraction finds phase abundances down to a typical normalized fraction of around 0.1 wt%.

Sometimes it is possible to calculate chemical (element) concentrations, by quantifying atomic compositions of discrete phases. For example, as lead does not form a solid-solution with copper, neutron diffraction can determine lead contents by quantifying the segregated metallic phase in a copper alloy object. In steel, for instance,

carbon is present as an intermetallic compound, cementite, containing 6.7 wt% carbon. Neutron diffraction measures the cementite phase in a volume of steel, which is then translated into the bulk chemical composition of weight percent carbon. Furthermore, binary alloy compositions can be derived by accurate lattice parameter determination, by Rietveld refinement of the unit cell expansion due to incorporation of the alloying element (e.g., Sn in Cu; C in Fe; P in Fe; Cu in Au or Ag) (Siano et al. 2006).

Residual strains and microstrains in metal objects are determined, for instance to reveal cold-working of a copper alloy artifact. Structural defects such as atom vacancies, presence of inclusions, and lattice defects may be responsible for local distortions and lattice deformations. Defects, microstrains, and residual strains are induced by mechanical, thermal, and chemical processing conditions, while slow heating and annealing may reduce crystal defects and relax lattice strains. Diffraction and ensuing reflection line profile analysis provide indications of such working processes, particularly useful if microstructural trends are revealed by comparison with suitable reference samples that are produced in a controlled way. Quenching and tempering of steel can be detected, as these treatments produce distinctive changes in the neutron diffraction pattern with regards to Bragg peak shifts and Bragg peak broadening.

The mutual orientations of grains can be analyzed by crystallographic texture analysis on a neutron diffractometer. Neutron texture analysis determines the orientations of crystallites in a statistical sense for the interrogated gauge volume inside an object. If the grains are oriented at random and if all grain orientations are equally realized then the material is said to be free of texture. Texture is an important material characteristic of metals and ceramics. Since texture is usually a result of solidification and manufacturing, it can contain information about the production history of an object. The method allows evaluation of the orientation distribution function (ODF) based on the measurements and analysis of a multitude of diffraction patterns collected at different scattering angles. The texture manifests itself as intensity variations of Bragg peaks as a function of scattering angle. Neutron texture analysis permits fast analysis of the ODF

for a single analysis point in several minutes. With respect to conventional metallography, the texture information seen by neutron diffraction is complementary and highly significant from the point of view of grain statistics because of the large number of crystals contributing to the diffraction signal and from the point of view of three-dimensional (3D) sampling of an object. Quantifying grain orientation distributions by neutron texture analysis is particularly relevant for metals, in order to reconstruct their thermal and working history (Artioli 2007).

Neutron diffraction is not normally applied to glassy and amorphous materials. The method is also inapplicable if spatial information of just a few microns is required. Neutron diffraction methods are limited to millimeter-sized spatial resolution and minor (not trace) phase fraction contents. Although the neutron diffraction beam is relatively large and many cubic centimeters of a material are analyzed, it is of low intensity, so that long measurement times are needed compared to X-ray diffraction analyses.

Small angle neutron scattering (SANS) requires a different neutron diffraction setup. SANS is based on elastic neutron scattering of thermal neutrons. Porosity of a material and size and surface characteristics of mineral aggregates can be studied. The method probes larger-scale structures, however, on extracted, typically small samples.

ToF neutron imaging setups at spallation sources can map structural parameters through analysis of Bragg edges via energy-dispersive neutron radiography. This technique is connected to neutron diffraction via Bragg-edge transmission analysis (Santisteban et al. 2001). It makes use of the fact that the transmission varies because neutrons are removed from the primary beam due to Bragg scattering, producing sharp Bragg-edge features. The method uses a broad neutron wavelength distribution at a pulsed source, with a time-resolving neutron imaging camera behind the object. The Bragg edges are mapped with a spatial resolution in the range of 0.1 mm and analyzed with Rietveld-type approaches in terms of positions, widths, and heights of the edges. These parameters can then be translated into phase, strain, and texture parameters of the material, and neutron radiography and tomography techniques can be employed to obtain 2D and

3D maps. It is anticipated that this emerging method will extend the use of neutron diffraction techniques for archaeological science.

Neutron methods do not mark, heat, or alter the object. There is a short-term activation, but, generally, the activation is low and short-lived. Copper alloy objects, for example, are typically active up to three days after analysis before being cleared for return to the owner, depending on thickness and composition. Iron artifacts are generally not active at all after analysis. Decay of activation is slower for certain elements such as cobalt, silver, gold, manganese in iron, and tin in copper. After around two hours of exposure to neutrons, a manganese-containing object, for instance, might need two to three days before it can be cleared for return.

In summary, neutrons penetrate inorganic objects better than X-rays, for instance allowing analyses of thick lead, leaded-bronze, and iron objects. Neutron diffraction can be used to detect and characterize metal under thick corrosion layers in a nondestructive way, without special sample preparation. The bulk composition, texture, and microstructure of the metal are determined independent of the corrosion, albeit with limited spatial resolution of a few millimeters.

Neutron diffraction is used in the study of archaeological finds and collections research in conjunction with other nondestructive methods such as radiography. The technique provides data complementary to that obtained by conventional analytical methods, such as optical and scanning electron microscopy, and X-ray diffraction of mineral phases. Well-characterized standards that have been produced according to ancient technological practices should be analyzed alongside the archaeological material. A conservator, conservation scientist, or archaeological scientist specializing in the material should be closely involved from the proposal stage through to the practical application of neutron analysis of archaeological objects.

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Neutron Radiography and Tomography

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Archaeological samples and objects from our heritage are often unique and are highly important for understanding the past. If they are investigated for scientific reasons in order to derive information about composition, age, conservation status, or hidden structures, such investigation should be carried out nondestructively and noninvasively. In this way, the often valuable objects are protected and available for future generations.

There are several methods established for this purpose, which have advantages but also limitations. This entry focuses on neutron imaging techniques, which have progressed a lot in recent years and been made available also for the study of archaeological objects. We compare in some cases these neutron methods with similar studies using X-rays. The X-ray approach is more common and has been in use for many decades (see X-RAY RADIOGRAPHY and X-RAY TOMOGRAPHY).

While neutron imaging techniques can compete in image quality today, the contrast and the information obtained from them is complementary to X-ray data. This is because of the differing interaction mechanisms of each radiation method. The principles of the two methods are described in more detail below.

Both X-rays and neutrons have the ability to transmit radiation through most materials with a probability that depends on the thickness, composition, and interaction rate (macroscopic cross-section) of the materials involved. Because X-rays interact exclusively with electrons in the atomic shell, the attenuation is increased much towards heavier elements. Since neutrons interact only with the atomic nuclei by absorption and scattering in a completely different manner, no dedicated rule for the different isotopes can be formulated. Generally, lower mass materials

(H, B, Li, and so on) can deliver much higher contrast than X-rays can provide, while many heavier materials (Pb, Bi, Pt, W, and so on) are much more transparent for neutron beams (see NEUTRON RESONANCE ANALYSIS (NRA)).

Using these properties of the two kinds of radiation in the right manner, samples can be analyzed easily in the radiography mode, where a shadow image is obtained using a suitable detector device. The example in Figure 1 illustrates the differences in neutron and X-ray transmission, while the inherent image quality is identical. With the X-ray image, the metallic parts are pronounced, while the wooden handle only becomes visible with the neutron image. Both datasets together will deliver the whole picture. A complete three-dimensional structure analysis can be obtained by the tomography approach (see details below).

Neutron beams with suitable intensity and beam quality can only be found at large-scale facilities, either reactor based or with accelerator-driven spallation sources. Thermal and cold neutrons are preferred due to the interaction rates and the options for highly resolved images with best possible image contrast. Such sources are huge installations, a long way from being mobile. Samples have to be transported from the museum and back. Their operation is organized according to a “user laboratory.”

Methodological aspects

Sources and detectors: practical imaging conditions

In order to obtain image data of the quality shown in Figure 1, the beam from the source has to be tuned by collimation. Both X-rays and thermal neutrons cannot be influenced much by optical elements or by magnetic fields. The collimator is used to select and separate the most suitable beam components. In the best case, the beam is parallel and uniform and has an equal spectral distribution. Its size (field-of-view (FOV)) should

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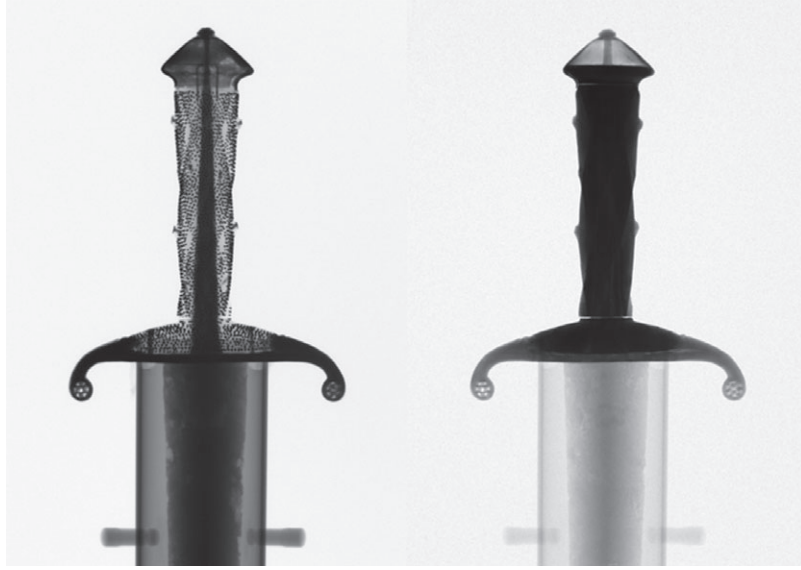


Figure 1 X-ray (left) and neutron (right) radiography images of a fifteenth-century sword from Oberwil (Canton Zug, Switzerland), in which the different contrasts for metallic parts and wood are demonstrated.

fit the object's dimensions. Since these conditions are never fulfilled perfectly, some compromises and corrections have to be made.

After passing through the object, the residual beam component is observed by using a two-dimensional detector, optimized for the particular kind of radiation. While X-rays can be detected directly, neutrons have to be converted first into an ionizing kind of radiation by a nuclear reaction, for example, capture in Li-6 or Gd-157 (see NEUTRON RESONANCE ANALYSIS (NRA)). In the past, a specific kind of film was used which had to be developed in a chemical process after exposure. Therefore, the “frame rate” was in the order of two images per hour only. In the meantime, several electronic detection systems have been developed and put into practical use (Mannes et al. 2015). Most common nowadays are systems with a combination of scintillators and highly efficient cameras, optimized for either high spatial resolution (Lehmann et al. 2004), large FOV, or high temporal resolution (Lehmann et al. 2007). Advantages of the digital imaging systems are the options for post-processing and image correction, much lower exposure time (less sample activation in the case of neutrons), flexibility in relation to FOV and resolution, and direct

quantification of the image data, for example, in the tomography reconstruction process.

Tomography: accessing the third dimension

Digital transmission data are structured in pixels as a two-dimensional matrix of gray values. Assuming Beer–Lambert's attenuation law can be applied for the transmission process, the attenuation coefficient Σ can be derived for each pixel, comparing the intensities with (I) and without (I_0) sample, related to the thickness d in beam direction z :

$$\Sigma(x, y) = \ln \left(\frac{I_0(x, y)}{I(x, y)} \right) / d(x, y) \quad (1)$$

Deriving attenuation coefficient values $\Sigma(x, y, z)$ for the third dimension also requires projections of the object from all directions (100 ... 1,000) and a mathematical algorithm for volume retrieval. Such an algorithm is based on the radon transformation of the projection data and a filtered back-projection into the voxel matrix. In the simple case of a parallel beam, the reconstruction with modern tools using advanced computer

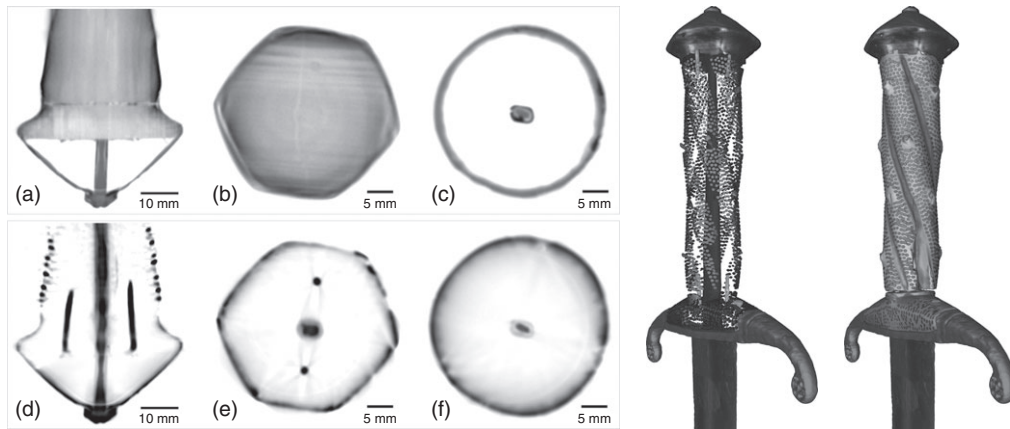


Figure 2 (Left) Virtual slices through the lower part of the sword handle: upper row (a, b, c), neutron tomography data; lower row (d, e, f), X-ray tomography data. The wood structure is visible in the neutron data, and metallic parts are pronounced by the X-ray data.

Source: Mannes et al. 2015. (Center and right) Outer tomography views of the X-ray data and neutron data, respectively, with metallic decorations of the wooden handle pronounced.

power can be done in a few minutes, depending on the data volume (number of pixels). Since high-resolution detectors provide already 2048 pixels in one direction, the resulting voxel matrix is in the order of 17 GB (gigabytes). This is not a real problem for data storage today but for the visualization steps in the data treatment, because the computer memory has to be in the order of twice the data volume for manipulation and tuning. In the case of a conical beam, the reconstruction algorithm is more demanding, for instance, using the Feldkamp algorithm.

The result of a reconstructed tomography dataset is a stack of tomograms, that is, slice images perpendicular to the rotation axis. This stack of images represents a three-dimensional volume data, which can be virtually sliced in any direction. The results can be presented in different ways. Tomography slice images deliver important information (cf. Figure 2) (Mannes et al. 2015). As shown in Figure 2 with the case of the sword from Oberwil (Figure 1), it is possible to give a perspective view of the tomography data by volume rendering provided by dedicated software tools.

If the three-dimensional material distribution is known, it is also possible to derive the material thickness from the precision of the detector resolution. This has been performed in the case of the famous golden bust dedicated to the Roman emperor Marcus Aurelius found near the former

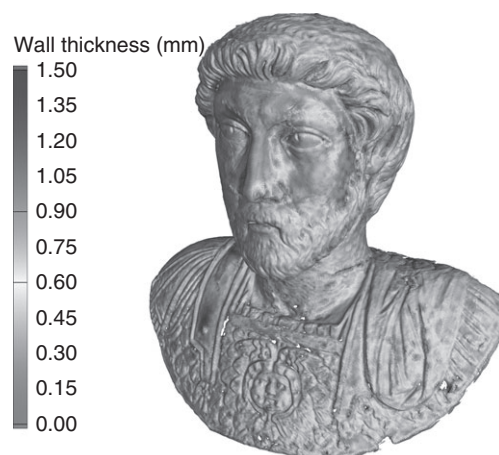


Figure 3 Wall thickness determination from tomography data of the Marcus Aurelius bust from Avenches. The object is 33.5 cm high, hollow, and contains nearly 1.5 kg of pure gold.

Source: Republished with permission of the *Journal of Roman Archaeology*, de Pury-Gysel et al. 2016.

settlement Aventicum (now Avenches, Switzerland). The gold distribution with respect to the wall thickness is color-coded for the whole object in Figure 3. This information gives insight into the manufacturing process in Roman times (de Pury-Gysel, Lehmann, and Giumlia-Mair 2016).

Application to heritage objects

Selection of the most suitable setup for investigations

Requests to study museum objects in either radiography or tomography mode are versatile. It depends on the composition and size of the sample which kind of radiation and which particular methods, facility, detection technique, and observation strategy are applied. In many cases, a combination of methods is preferable (radiography and tomography; neutrons and X-rays; diffraction (see NEUTRON DIFFRACTION (ND)) and imaging (see IMAGING)).

Generally, transmission and contrast limit the chance of a successful study. Based on the tabulated cross-section data Σ for thermal neutrons and μ for X-rays, respectively, the layer thickness for the remaining 2 percent transmission $d_{\max}$ can be estimated in advance of a real experiment (where N is the nuclear density of the involved materials and σ is the microscopic cross-section):

$$d_{\max} = \frac{3.91}{\Sigma} = \frac{3.91}{\sigma \cdot N} \quad (2)$$

The minimum distinguishable material layer for a specific material can be derived in a similar manner when a 2 percent contrast difference is analyzed:

$$d_{\min} = \frac{0.02}{\Sigma} = \frac{0.02}{\sigma \cdot N} \quad (3)$$

There are several tricks and options (e.g., different energies of the radiation) to overcome these limits in some respect, but not by orders of magnitude. As a first guideline, equations 2 and 3 are well applicable.

As well as the transmission and contrast issues, the dimensions of the objects have to fit the beam size and the detector's FOV. Neutron beams up to 40 cm in diameter are available, while the highest resolution of only 5 μm can be achieved with 1 cm^2 FOV. This gives high flexibility to perform different studies.

Advanced neutron imaging methods

Many studies have been performed successfully using radiography and tomography methods. However, neutron beams can also be used in

an advanced manner for specific and dedicated investigations.

In the case of the neutron imaging facilities at the Paul Scherrer Institut, Switzerland, the beam is delivered from the source in a broad spectrum (Maxwellian distribution) either at around the average energy of 25 meV (wavelength 1.8 Å) for thermal neutrons or at an even lower mean energy of about 3 meV for cold neutrons. Most structural materials are microcrystalline with different grain size and orientation (texture). Each crystal structure corresponds to a Bragg scattering feature that is visible as far as the sharp edge given by the scattering conditions according to Bragg's law (see DIFFRACTION).

Energy-selective imaging becomes available when the spectrum is reduced to a narrow band where the crystal orientations can be observed individually. Technically, this band selection is performed by means of turbine-type selectors or double-crystal monochromators with a resolution between 2 and 15 percent in the wavelength. Even higher resolution can be obtained with a time-of-flight approach using pulsed neutron sources. Such methods have been applied successfully to studies on ancient Japanese swords (Salvemini et al. 2012). It is particularly important in the study of ancient welds, to see how they were done—nondestructively.

Diffraction neutron imaging is a technique where an object is investigated not only in the transmission mode but also with simultaneous observation of the diffracted component. These data can be used to provide information about the crystalline structure of the object too; larger crystal zones will deliver brighter spots in the diffraction image. This method is still under development but has great potential for noninvasive material characterization.

Neutron grating interferometry, in particular the use of the “dark-field” signal, has been implemented recently and can be used as a tool for material characterization with respect to inclusions or mixing phenomena in the order of micrometers.

Data fusion between neutron and X-ray images can be done with a second source included in the neutron imaging facility, where images of the object are obtained either simultaneously or sequentially with the same pixel matrix but a different image contrast (Mannes et al. 2015).

The corresponding evaluation procedures are the subject of current development.

Data analysis and image processing

Modern neutron (and X-ray) imaging techniques are based on digital detectors. Therefore, the whole branch of common image processing tools is applicable. However, for full usage of the image information, knowledge is required of how the image is produced, which inherent image distortions and artifacts are induced, and how to correct such effects in the best way possible in order to avoid quality reductions. This is particularly important in the application of very old samples, where often no template, copy, or pre-description are available. These unique objects have to be analyzed carefully both qualitatively and quantitatively.

Tools and procedures

Digital data from the transmission measurements should be in a format with a wide dynamic range (at least 16 bits), with a linear response to the attenuated signal, and readable by standard tools (ImageJ, IrfanView). Today, such freeware tools are available to and useful for normal users with experimental beamlines. As well as this approach, programs like IDL and Matlab are useful for large series of data treated under identical conditions. Some programming in different languages (C++, Java, and so on) is required in special cases where standard tools are not flexible or powerful enough. In the case of tomography reconstruction and visualization, useful tools have been built, but mostly are only commercially available.

Limits in quantification

The transmission data from the imaging process can be used for the quantification of the sample's content in the first order only. Using Beer–Lambert's law in equation (1), the image data $I(x, y)$ can be related to the “open beam” data $I_0(x, y)$, and by knowing the sample thickness, the content information can be derived. However, due to scattering effects which induce directional

and spectral changes of the transmitted component, a deviation of the conditions assumed in equation (1) can happen. It depends on the importance of the scattered part of the beam how much the quantification process is disturbed. There are several approaches to overcome the situation using correction tools or special experimental procedures (Hassanein, Lehmann, and Vontobel 2005).

Data handling and archiving

As it becomes more and more common to perform digital imaging using either X-rays or neutrons for museum objects, the data storage, exchange format, and final archiving are highly important. The data volume, driven by the higher pixel density of the sensors, is in the megabyte range for simple radiography, but reaches gigabytes to terabytes in the case of tomography and time sequences. It will be an important work in itself to define the most suitable data formats (without loss of information) and long-term available storage devices for all data obtained today and in the near future. Some pioneering work is being done in the framework of national and European projects.

Conclusion

In summary, neutron and X-ray imaging methods are valuable tools for noninvasive studies of museum objects and archaeological and paleontological samples. While X-ray facilities are available at many laboratories, neutron beam lines are linked to a limited number of large-scale facilities. In the case of the Paul Scherrer Institut, both methods are combined in one facility. Access to the large-scale facilities is in most cases organized via a proposal procedure, where research applications are ranked and beam time is delivered accordingly.

The outcomes of neutron (and X-ray) studies are images in 2D and 3D with the specific contrast of the applied radiation. Experts in archaeometry and cultural research need to learn how to evaluate and interpret the data, including the extraction of numerical information.

SEE ALSO: X-Ray Radiography and Material Analysis

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Neutron Resonance Analysis (NRA)

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Neutron resonance analysis (NRA) is very suitable for obtaining bulk elemental compositions of archaeological objects. It is based on two methods: one (NRCA) on capture spectrums and the other (NRTA) on transmission through the object.

Neutrons can lead to various kinds of reactions when they interact with nuclei. Since the neutron is an electrically neutral particle, it can enter the nucleus easily, forming a new, highly excited (compound) nucleus of the same element but with an additional neutron. The compound nucleus can either re-emit a neutron, which is effectively a scattering process, or it can emit prompt gamma-rays (γ -rays), or in the case of some heavy nuclides, it can induce fission. The latter is not of interest for the current discussion. The strength of these reactions as a function of neutron energy shows peaks. They are related to excited states of the compound nucleus and are known as “resonances”.

Resonances occur at energies that are specific for each nuclide and can be considered as “fingerprints” of elements and/or isotopes. Thus, elements can be identified on the basis of resonance energies in a neutron spectrum, while areas of resonance peaks provide information about the elemental (or isotopic) composition. It is clear that this way of detecting elements requires a source of neutrons over a wide energy range.

To determine the energy of a neutron that interacts with a nucleus, the *time-of-flight* (TOF) technique is a convenient method. With this technique the neutron velocity ($v = L/t$) is determined from the time (t) a neutron needs to

travel the distance (L) from the neutron source to the object positioned in the neutron beam. For non-relativistic applications, the neutron energy is given by $E = \frac{1}{2}mv^2$ with m being the neutron mass.

For timing the neutron, a start pulse from the neutron source and a stop pulse from the detection of the neutron is needed. This requires a pulsed neutron source. For instance, the neutron source of the GELINA facility operated by the Joint Research Institute of the European Commission (EC-JRC) in Geel (Belgium) can be used for such experiments. A pulsed electron beam is accelerated to a maximum energy of about 140 MeV and impinges on a uranium target. The resulting “Bremsstrahlung” produces neutrons mainly by photonuclear reaction. Another important kind of a pulsed neutron source is located at the ISIS facility of the Rutherford-Appleton Laboratory in Harwell, UK. This source is based on spallation of nuclei by high-energy protons. More about the TOF technique can be found in Schillebeeckx et al. (2012).

Observation of resonances as a function of neutron energy leads to neutron resonance analysis (NRA), for which two detection methods can be applied. In one method, the prompt γ -rays emitted after neutron capture are detected. This is referred to as *neutron resonance capture analysis* (NRCA). This method requires γ -ray detectors with a good time resolution, which are positioned near the artifact in the neutron beam. Neutron resonances are also visible in a neutron spectrum measured after the transmission of a neutron beam through a sample, again as a function of neutron energy. This requires a neutron detector placed at a distance behind the sample. Neutron transmission spectrums show dips at certain resonance energies, on which the *neutron resonance transmission analysis* (NRTA) method is based.

Related analyzing methods are neutron activation analysis (NAA) based on the remaining activity after neutron capture (see NEUTRON ACTIVATION ANALYSIS (NAA)), and prompt gamma-ray analysis (PGA) based on the detection of prompt γ -rays of specific energy.

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NAA and PGA require intense (sub)thermal neutron beams interacting with the objects. For NAA, activation of the object is an essential part of the method. In the case of PGA, it is an unwanted aspect. With NRCA, activation is low due to a high detection efficiency, while activation is further reduced by removing low-energy neutrons with a high activation probability, by using suitable filters.

Neutron cross-sections

The probability of a nuclear reaction is expressed as an effective area known as the cross-section, and denoted by σ . The standard unit for measuring a nuclear cross-section is the barn, with $1 \text{ b} = 10^{-28} \text{ m}^2$. Resonance structured cross-sections can be parameterized in terms of resonance parameters. For an isolated single resonance it is the sum of a pure resonance part, a contribution due to potential scattering, and an interference term between resonance and potential scattering. The contribution due to scattering from the nuclear potential is a smooth function of energy. In the low-energy region it can be approximated by $\sigma_{\text{pot}} = 4\pi R'^2$ in which R' is the effective nuclear radius. Normally, potential scattering is small compared with resonance scattering, and the influence on the shape of total resonance cross-section (scattering plus capture) is often negligible. In the Single Level Breit Wigner (SLBW) approximation, the resonance part of the total cross-section in the region of a single neutron resonance is of the form $\sigma_0/(1+x^2)$, in which $x = 2(E - E_\mu)/\Gamma$, E_μ is the central energy of the resonance, Γ is its width at half-height, and σ_0 is the maximum value of the resonance part. The total width is the sum of the partial widths of all open reaction channels. In case only neutron capture and elastic scattering are possible, the total width is $\Gamma = \Gamma_n + \Gamma_\gamma$. The partial neutron (Γ_n) and gamma widths (Γ_γ) are related to the relative probability that an elastic scattering and capture reaction, respectively, occurs. The neutron width is also a measure of the probability of forming the compound nucleus. The capture cross-section in SLBW in the region of a single resonance is the resonance term of the total resonance cross-section multiplied by the fraction Γ_γ/Γ .

For most of the elements, cross-sections show a large number of resonances in the energy region below 10^4 eV . Exceptions are those of the lightest elements and elements with both the proton and neutron numbers close to the so-called “magic numbers”. Neutron resonance analysis (NRA) can therefore be carried out for a large number of elements (isotopes) in the neutron energy range between 1 eV and 10^4 eV .

The observed neutron resonance profiles are modified compared with the SLBW expression. This is due to several effects, namely:

1. Broadening by thermal motion. This requires a convolution with the thermal distribution function, which leads to the *Doppler broadened cross-section* $\sigma_\gamma^D(E)$.
2. The finite time resolution of the TOF spectrometer.
3. In the case of NRCA, reduction of the beam intensity. In the region of strong resonances, this effect, known as resonance self-shielding, will result in a large reduction in the intensity.
4. In the case of NRCA, neutron scattering (once, twice, or even more) inside the object before capture. Since the energy lost by neutrons during scattering depends on the scattering angle, broad structures may arise on the high-energy sides of resonances due to such multiple interaction events.

The original resonance has a Lorentz shape, while for most applications the thermal distribution function is Gaussian-shaped. As a consequence the Doppler broadened cross-section can be approximated by a Gaussian shape around the central energy and a Lorentzian shape at the wings.

Neutron resonance capture analysis (NRCA)

The main parameter of interest for NRCA application is the integrated area (A_γ) of the capture resonance peak. The integrated resonance area (A_γ) in the case of a neutron capture reaction, expressed in barn.eV, is:

$$A_\gamma = 4.097 \times 10^6 ((M + m)/M)^2 g_I \Gamma_n \Gamma_\gamma / E_\mu \Gamma \quad (1)$$

where m is the mass of the neutron, M is the atomic mass of the interacting nucleus, and the term g_f is related to the coupling of the particle spins. The resonance energy E_μ and resonance widths ($\Gamma_n, \Gamma_\gamma, \Gamma$) are expressed in eV. While Doppler broadening lowers and widens a resonance, it does not change the resonance area.

The number of integrated capture counts N_μ observed in a resonance μ at energy E_μ in a homogeneous and flat object is given by (Postma and Schillebeeckx 2010):

$$N_\mu = \varepsilon_\mu F_\mu A_{\gamma,\mu} a_\mu n_x \Omega \Phi(E_\mu) \quad (2)$$

Here ε_μ is the detection efficiency for the prompt γ -ray at this particular resonance, F_μ is the self-shielding factor integrated over the resonance, $A_{\gamma,\mu}$ is the area of the capture resonance, a_μ the isotopic abundance, Ω the area of the sample illuminated by the beam, $\Phi(E_\mu)$ the time-integrated neutron flux at the resonance, and n_x the total number of nuclei per unit area of element X. Multiplying n_x with the atomic mass of element X gives the amount of weight (W_X) observed in the part of the object illuminated by the beam.

To extract the number of nuclei from the number of counts, all the other quantities in the expression for N_μ need to be known. Unfortunately, the detection efficiency ε_μ , solid angle Ω and absolute neutron flux are very difficult to determine accurately. A direct use of the relationship also requires knowledge of the resonance areas, which is not always available. In addition, archaeological artifacts mostly have a complex shape, which requires integration of the above expression over the illuminated part of the object, making absolute corrections for self-shielding and multiple interactions difficult. Therefore, a more empirical approach is mostly applied. Applying this approach, referred to as the *double ratio method*, several of the parameters cancel. The ratio of the weights W_X and W_Y of the elements X and Y in an object is obtained from the ratio of counts N_X and N_Y , by comparing with the same ratios of a known calibration sample:

$$\frac{W_X}{W_Y} = K_{\mu,\lambda}^{cal} \frac{F_\lambda N_\mu}{F_\mu N_\lambda}, \text{ with } K_{\mu,\lambda}^{cal} = \left(\frac{F_\mu N_\lambda W_X}{F_\lambda N_\mu W_Y} \right)_{cal} \quad (3)$$

The calibration factor $K_{\mu,\lambda}^{cal}$ can be obtained from measurements of calibration samples with a known composition and thickness. The self-shielding factors, denoted by F , can be calculated with the aid of known total cross-sections. Often for each element, several resonances with different strengths can be observed. This leads to the possibility of analyzing data with a number of pairs of resonances. The effective areal density of the main element, which is required for the calculation of the self-shielding factors, can be derived from a least squares analysis. Using the areal density as a free parameter, consistent weight ratios can be obtained; see, for instance, the analysis of the Buggenum sword (Postma et al. 2010).

An important step in the analysis is the extraction of the number of counts in resonance peaks. In the case of an isolated resonance that is free from overlap with other resonances and a simple background, it can be done by summing the counts of the channels of the peak by setting limits as far out in the wings as possible and by subtracting the background component. It becomes more complicated if the resonance has a strong structure due to multiple interaction events (scattering followed by capture) or if overlap with other resonances occurs. In such cases a shape analysis should be carried out: either a relatively simple shape analysis based on pseudo-Voigt functions, or on more complicated codes like REFIT (Moxon and Brisland 1989).

Neutron resonance transmission analysis (NRTA)

When a neutron traverses an object, neutrons are removed by capture and scattering interactions. As a consequence, the spectrum after transmission will show dips at resonance energies. Again, elements can be recognized from the locations of the resonances, while the areas of the dips provide information about the amounts of these elements.

NRTA requires a neutron-sensitive detector. A suitable neutron detector is a Li-glass scintillator that is enriched in ^6Li , which has a large capture cross-section for the reaction $^6\text{Li} + n \rightarrow ^3\text{H} + ^4\text{He}$. The energy of this reaction generates a light flash (scintillation) in the glass, which is detected by a photomultiplier viewing

the Li-glass. Experimentally the transmission is obtained from the ratio of the result of a sample-in and sample-out measurement, both corrected for losses due to dead time and background contributions. Since the experimental transmission is a ratio of TOF-spectra obtained with the same detector and in the same geometry, it is an observable that is independent of the detector efficiency and neutron flux. Ideally the measurements are performed in a good transmission geometry such that the experimental transmission is almost a direct measure of the theoretical transmission, which is given by:

$$T(E) = \exp\left(-\sum_k n_k \sigma_{tot,k}^D(E)\right) \quad (4)$$

where $\sigma_{tot,k}^D$ is the Doppler broadened total cross-section and n_k is the areal number density (or number of atoms per unit area) of nuclide k in the sample. Measurements in good transmission geometry can be realized by properly collimating the neutron beam such that all detected neutrons have traversed the sample and neutrons that are scattered by the sample are not detected. Under these conditions the composition of the sample can be derived absolutely without any calibration requirement (Schillebeeckx et al. 2014). This is one of the main advantages of NRTA compared with NRCA. In the 100 keV to 1 MeV region, NRTA can also be applied to determine the amount of light elements. In addition, using a position-sensitive neutron detector, NRTA can be a useful basis for an imaging method with element recognition based on resonances (Perelli Cippo et al. 2011). On the other hand, the sensitivity of NRCA to detect impurities and trace elements, even in the ppm region, is much higher. This is discussed below.

TOF resolution

The experimental observable of both NRCA and NRTA measurements will be broadened due to the finite time resolution of the TOF spectrometer, and in the case of NRTA, of the neutron detector. Evidently the impact of the corresponding response functions decreases with increasing flight path distance. The response function of both the TOF spectrometer and neutron detector

can be derived from Monte Carlo simulations. The former is primarily determined by the neutron transport in the target-moderator assembly. In general, the TOF resolution of a pulsed neutron source based on photonuclear reactions is superior compared with the one based on spallation reactions (Schillebeeckx et al. 2014). The response function at a spallation source is more complex. In addition, their response functions have more asymmetric shapes and are affected by a contribution with a long tail.

The response of the neutron detector is strongly dominated by the attenuation of the neutron beam in the neutron-sensitive material of the detector; for example, the response of a Li-scintillator neutron detector is defined by the thickness of the ${}^6\text{Li}$ -glass.

Example of NRCA and NRTA applied together

As an illustration of NRCA and NRTA, an example in which both methods were applied is presented. It concerns a fragment from a cauldron, a seventh century BCE Etruscan bronze vessel, excavated in Satricum, 60 km south of Rome. Spectrums of both methods are shown in Figure 1. In the capture spectrum, resonance peaks are observed, while these resonances appear as dips in the transmission data. The most prominent peaks and dips are due to resonances of copper, tin, arsenic, antimony, silver, and indium.

The ratio of counts in two resonances of the same element varies with the thickness of the object, in the case that self-shielding effects are different (that is, when a weak resonance is compared with a strong resonance). This occurs for the resonances of copper at 230 and 578 eV. With a calibration curve, obtained with a series of copper sheets of several thicknesses, an areal density of 0.54 (4) g/cm² for Cu was derived from the capture data. (Postma et al. 2003). This areal density is in good agreement with the value of 0.55 (2) g/cm² obtained from transmission data. The latter was obtained without the need for any additional calibration data.

Weight ratios $W_{\text{Sn}}/W_{\text{Cu}}$ and $W_{\text{Ag}}/W_{\text{Cu}}$ derived from NRCA and NRTA measurements are compared in Table 1. They are in good agreement. The uncertainties are only due to counting statistics.

Table 1 Composition of the *cauldron* fragment as determined by NRCA and NRTA. The quoted uncertainties are only due to a propagation of counting statistics uncertainties.

Method	Weight ratio			
	W_{Sn}/W_{Cu}	W_{As}/W_{Cu}	W_{Sb}/W_{Cu}	W_{Ag}/W_{Cu}
NRCA*	0.2681 (13)	0.004333 (16)	0.00252 (27)	0.00114 (9)
NRTA**	0.243 (7)			0.001112 (10)

* calibration method, ** absolute determination

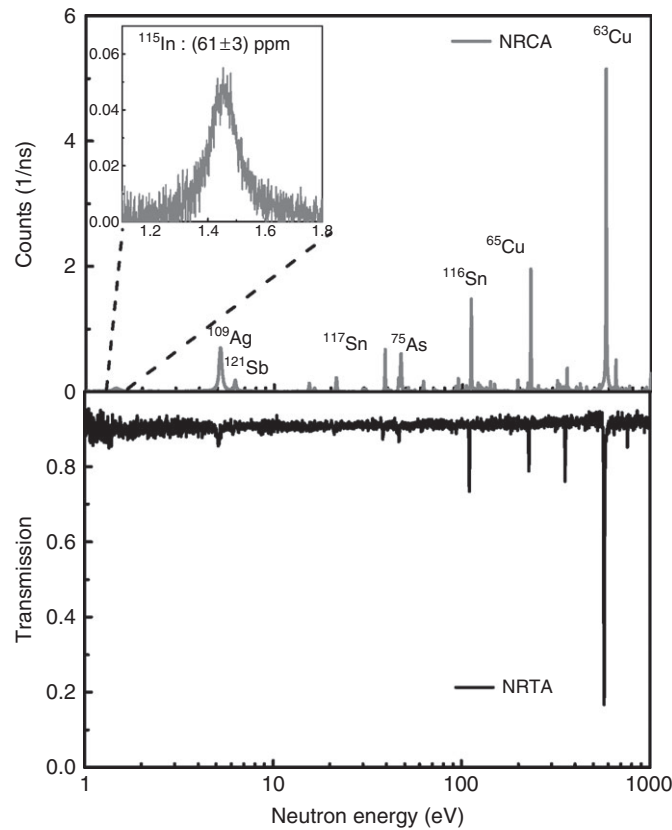


Figure 1 Capture and transmission spectrums obtained at the GELINA facility as a function of neutron energy for the cauldron sample. For the capture measurement, a flight path of 12.5 m was used. The transmission experiment was carried out at a station with a 10 m flight path. Elements with isotopic numbers are indicated at several resonances which were used for the analysis. Published with permission of Springer, from Postma, Schillebeeckx, and Halbertsma (2004), “Neutron Resonance Capture Analysis of Some Genuine and Fake Etruscan Copper-alloy Statuettes.” *Archaeometry* 46 (4), 635–46.

The values derived from NRTA are obtained in an absolute way. However, they depend on the quality of the nuclear data, that is, the resonance parameters used in the analysis from Tsuchiya et al. (2014).

Figure 1 shows that a trace element such as indium can be detected by NRCA. The relative amount of indium, $W_{In}/W_{Cu} = 79 (4) \times 10^{-6}$, derived from the capture data is not sufficient to create an observable dip in the

transmission spectrum. In conclusion, NRCA has a more favorable detection limit to identify trace elements compared with NRTA. The advantage of NRTA is the absolute way to derive directly the amounts of elements in objects.

It has been shown in several of the NRCA projects that it is of value to implement information derived from X-ray or neutron diffraction (see NEUTRON DIFFRACTION (ND)) for the benefit of the analysis of archaeological objects (Schut et al. 2008; Postma et al. 2011).

Some NRCA results

NRCA has been successfully applied to various kinds of archaeological objects. Some of these results are briefly mentioned. For all the objects mentioned below, a sheet of cadmium was used to remove neutrons below 0.7 eV from the beam, and a sulfur disk was used to remove high-energy neutrons in order to reduce activation to a very low level. The objects could always be returned to the owners the same or next day after the run with negligible activation.

The first extensive study by NRCA concerned statuettes and some small parts from the famous collection assembled by the Count Corazzi of Cortona (Italy) in the eighteenth century. This collection is said to be from the Etruscan period. It now belongs to the National Museum of Antiquities in Leiden, the Netherlands. However, questions were raised concerning the origin of several of these items. For this reason, NRCA experiments were carried out on a series of these artifacts. It turned out, on the basis of their compositions, that five of them are from later times. They are fakes or imitations, possibly made during the Renaissance (Postma, Schillebeeckx, and Halbertsma 2004).

A study of parts of water taps excavated in the Netherlands showed the technical skills of the Romans in fabricating objects (Schut et al. 2008).

Several swords of the Middle Bronze Age were analysed. An extensive study of the Buggenum sword from the National Museum of Antiquities in Leiden should be mentioned, which also includes neutron diffraction (see NEUTRON DIFFRACTION (ND)) research (Postma et al. 2010).

A study of socketed axes of the Geistingen type showed that bronze objects are not always made from tin-copper alloy, but in this case they are made from a complex alloy containing large amounts of nickel, antimony and arsenic, together with about 25 wt.% in copper (Postma et al. 2011).

SEE ALSO: Archaeometry; Material Culture; Neutron Activation Analysis (NAA); Neutron Diffraction (ND); Neutron Imaging and Tomography in Conservation; PIXE and Material Analysis

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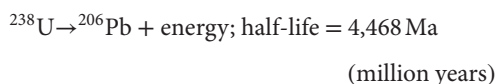
Non-Stable Isotopes in Archaeology

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Introduction to lead isotopes

Lead occurs in major amounts not only in lead–zinc–silver ore deposits, but also in lesser amounts in copper and iron ore deposits; it occurs in at least parts per million levels in all rocks and non-metallic minerals. Terrestrial lead consists of four stable isotopes: ^{208}Pb , ^{207}Pb , ^{206}Pb , and ^{204}Pb . The isotope ^{204}Pb is non-radiogenic in origin; it was incorporated into the Earth when it was formed from the proto-solar system about 4.57 thousand million (10^9 or billion) years ago. The other three lead isotopes (LIs) derive from the radioactive decay of longlived naturally radioactive isotopes of uranium (U) and thorium (Th):



At first U, Th, and Pb were uniformly mixed together in the hot, liquid Earth. When the Earth started to cool, the relative concentrations of these elements differentiated from place to place. During those years, the U and Th were continuously producing more of ^{208}Pb , ^{207}Pb , and ^{206}Pb , but in somewhat different amounts. A more important stage of differentiation of the amounts of the isotopes came with the process of ore formation starting about 3 billion years ago when, due to the high temperatures and differences in chemistry, U and Th were separated from lead. Therefore, in most minerals the U/Pb and Th/Pb ratios are so low that their lead isotopic compositions have not changed appreciably with time since it was

laid down in a mineral deposit. These “frozen” in time lead isotope compositions can be used for dating of the ore- and rock-forming processes.

If there are no additional events influencing the lead isotope compositions in the ore mineral or rock, then this system is referred to as single-stage radiogenic growth of lead in a closed chemical system. It can be characterized by growth curves with associated values of $^{238}\text{U}/^{204}\text{Pb}$, as measured today for the parent U–Pb system, and $^{232}\text{Th}/^{204}\text{Pb}$ ratios for the parent Th–Pb system. This model is called the Holmes-Houtermans model; its more developed versions were proposed by Stacey and Kramers, and Cummings and Richards (see Faure 1986). Using these mathematical models, it is possible to calculate, from the measured LI compositions of ore minerals, so-called “model ages” of the ore deposits. The growth curve of the LI ratios related to the age of the ore deposits is clearly represented on the plots of ratios of $^{206}\text{Pb}/^{204}\text{Pb}$ (x axes) and $^{207}\text{Pb}/^{204}\text{Pb}$ (y axes) (Figure 1a).

The isotope compositions of the lead in the ores depend on the age of their formation, the original amounts of uranium and thorium, and the further geological history of the deposit (mixing with ore-forming fluids, redeposition, later metamorphism). Therefore, in principle, minerals of different geographical origin, formed at different geological periods, have a high probability of displaying different LI compositions.

The measurements of lead isotope compositions

Since the 1970s a standard method used for LI analyses has been thermal ionization mass spectrometry (TIMS). The LI ratios are measured using exactly specified chemistry of lead separation and deposition, and methodology for running the mass spectrometer; the raw data are corrected by comparisons with lead isotopic standard US NBS (NIST) SRM 981. Strict adherence to this methodology allows us to measure LI compositions with very great accuracy (usually

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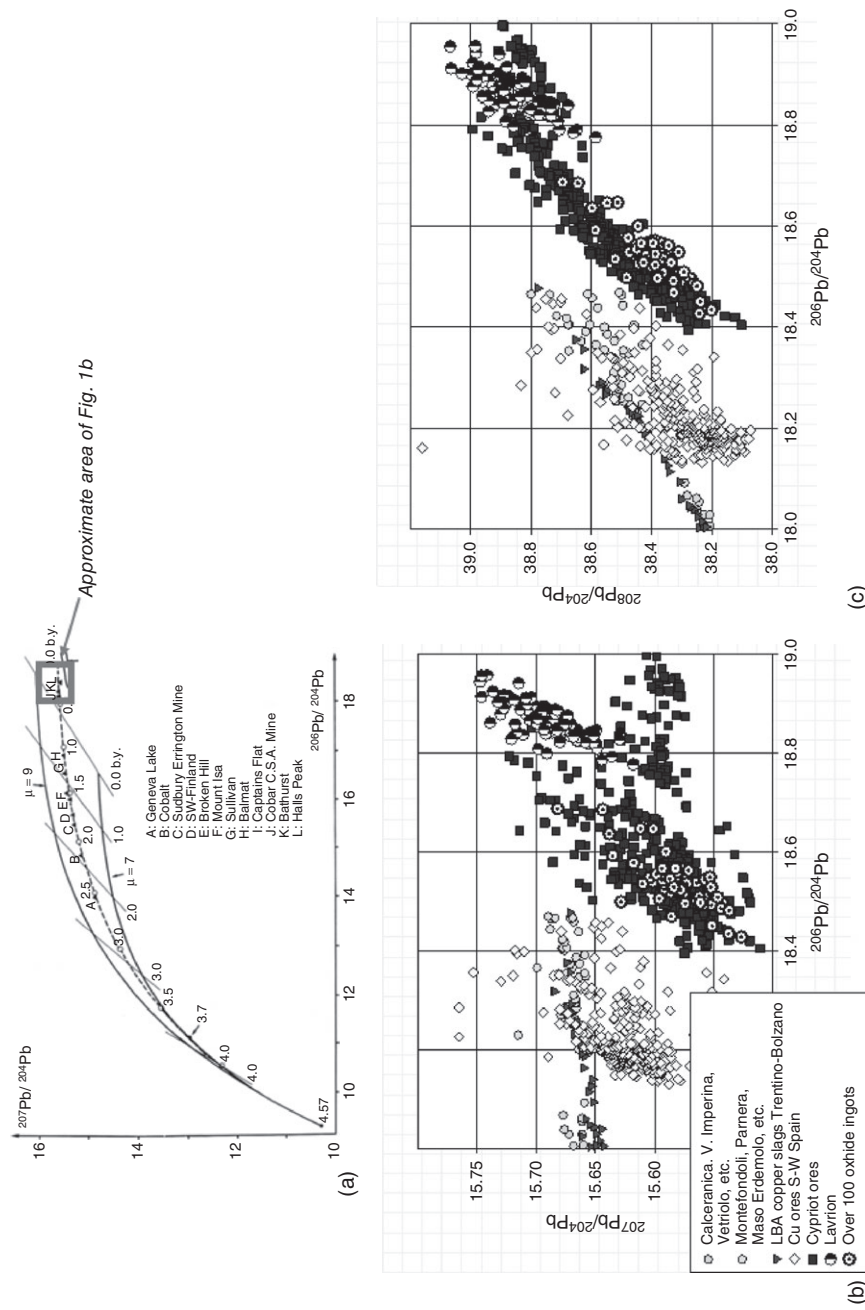


Figure 1 (a) Graphic representation of the Holmes-Houtermans model ages of ore deposits (A, B, C, etc.) calculated from their lead isotope ratios. This model demonstrates that not only ores of different ages, but also ores of the same age can have different lead isotope compositions due to the different initial amounts of uranium and thorium in the ore-forming fluids (μ values) represented by the outer curves. The straight lines indicate ores of the same age. (b) and (c) Plots of two sets of independent lead isotope ratios representing data for copper ore deposits in the Mediterranean, which were exploited in the Bronze Age, and the second millennium BCE copper ingots of the "oxide" shape that were found in Cyprus, Greece, Italy, Egypt, Turkey, and Bulgaria. All these ingots have lead isotope ratios and trace elemental compositions fully consistent with the Cypriot copper ores.

better than 0.1% for annual runs of the SRM 981 standard) and very good reproducibility of measurements taken in different laboratories.

Further developments in instruments measuring LI compositions came with the introduction of instruments that use laser ablation of the sample and ionization of lead in a plasma source with multiple Faraday cups as ion collectors: multicollector inductively coupled plasma mass spectrometers (MC-ICP-MS). These allow analyses of much smaller samples with very high overall accuracy (commonly 0.01%).

The TIMS and MC-ICP-MS are the only methods of measuring LI compositions that are suitable for archaeological provenance research. The other instruments that can measure the LI ratios (e.g., quadrupole mass spectrometer (Q-ICP MS) or time-of-flight (ToF) mass spectrometers) have much poorer accuracy due to substantially larger and less reproducible mass fractionation.

Application of lead isotope compositions in archaeology

In 1967 Robert Brill and John Wampler published comparisons of the LI compositions of ancient lead artifacts with those of ore deposits. Quite soon, LI provenance studies broadened to include analyses of glass, glazed pottery, silver coins, and artist's pigments. In 1982 the first paper was published suggesting use of LIs for finding sources of Bronze Age copper artifacts (Gale and Stos-Gale 1982), and that considerably raised the interest of archaeologists in this method for provenancing Bronze Age metals. In the following years archaeometallurgical projects conducted by several research groups developed the methodology by analyzing ores and metals to test the possibility of changes of lead isotope compositions during the smelting and refining processes, or during the addition of tin to make bronze. The results of these experiments proved that metallurgical processes do not change the original LI compositions of metals and pigments. Since the early 1980s several large research projects into sources of copper, lead, and silver in the Bronze Age were undertaken. These projects were based on simultaneous collection of mineral samples from ore deposits, and samples of ancient artifacts

from archaeological excavations and museums, combined with archaeometallurgical surveys of ancient mines and slag heaps, and provided LI, geochemical and chronological information about the earliest copper and lead/silver ore extraction in the Old World (e.g., Stos-Gale and Gale 2009; Artioli et al. 2014; Pernicka, Lutz, and Stöllner 2016).

Since there is a necessity to take small samples from artifacts for lead isotope analyses (1–20 mg), the scope of the research can be limited by the reluctance of museum curators and archaeologists to allow sampling of precious artifacts. For MC-ICP-MS it might be possible to use laser ablation from the surface of the artifact to minimize the damage, but there is no possibility of the use of a mass spectrometer in a museum or on archaeological site, since no machine of the required accuracy has yet been developed in a sufficiently portable format.

Methodology of interpretation of lead isotope data

The identification of origin of archaeological materials requires comparisons of their lead isotope ratios with the ores, and therefore an extensive lead isotope database for ore deposits is the most important requirement. Calculating the geological age (model age) from the lead isotope ratios of the ancient artifact and comparing with the known ages of ore deposits is not sufficient, due to the variations in lead isotope compositions of ores not related to their age (e.g., the U and Th contents and other geological processes). So far there is only one open LI database on the internet; OXALID makes available data for Mediterranean ore deposits and Bronze Age metals (University of Oxford 2017). The other datasets are still only available in published papers. Currently there are about 8,000 published lead isotope results for ores relevant to Old World archaeology.

In principle, the ancient artifact can be regarded as fully consistent with an origin from a given ore deposit if the three independent lead isotope ratios of the artifact are each identical to the lead isotope ratios of the ores from this deposit. So, the initial stage of identifying the possible sources of archaeological artifacts

relies on finding, for each artifact, the identical data for ores. This can be done by calculating the Euclidean distances between the three independent lead isotope ratios of the artifact and all available ratios for ore samples. However, this is only a preliminary step to select a group of ore deposits that have lead isotope ratios within the appropriate range. Following this initial selection, it is necessary to check the geochemistry and history of exploitation of the possible ore deposits and eliminate those which cannot have been used as a source of given material on geochemical or historical grounds.

Plotting the lead isotope ratios of the artifacts and ores on two lead isotope diagrams to include all three independent lead isotope ratios provides the most accurate visual representation of the consistency of lead isotope ratios of the ores and artifacts. The lead isotope ratios used for such plots in geochronology always relate to ^{204}Pb , as seen in Figure 1b and c: $X = ^{206}\text{Pb}/^{204}\text{Pb}$, $Y_1 = ^{207}\text{Pb}/^{204}\text{Pb}$ and $Y_2 = ^{208}\text{Pb}/^{204}\text{Pb}$. However, because the isotope ^{204}Pb in naturally occurring lead is always present in much smaller quantities than the other three radiogenic isotopes, the measurements of the ratios to ^{204}Pb are less accurate. Therefore, in principle, the plots of radiogenic ratios can show more accurately the comparative positions of data points. For this reason, in the research publications of archaeological applications of lead isotope measurements, most often the two plots represent the data along the axes: $X = ^{207}\text{Pb}/^{206}\text{Pb}$, $Y_1 = ^{208}\text{Pb}/^{206}\text{Pb}$ and $Y_2 = ^{206}\text{Pb}/^{204}\text{Pb}$. Some researchers also used other ratios, but essentially the choice of lead isotope ratios for comparative plots always leads to the same conclusions if all three independent ratios are considered.

Problems and additional help with interpretation of lead isotope data

Not all ore deposits have different ranges of lead isotope ratios, and therefore there are common instances of overlap of the data for deposits from different geographical regions. In such cases, there are two main points that must be considered: the geochemistry of the ores in each of the deposits, and the probability of their

exploitation in the period under consideration. Therefore, it is necessary to compare the elemental compositions of ancient artifacts with the geochemistry of the ores and the periods of exploitation of the selected ore deposits. The elemental compositions of metals reflect the type of ore mineral used for smelting, and typical impurities are often characteristic of certain deposits. Furthermore, the trace element signatures can discriminate metal groups that not only reflect various ore types, but are important for comparison with previously analyzed artifacts from various regions and certain chronologies. However, it is important to stress that the identical lead isotope characteristics of a group of metals do not guarantee that their elemental characteristics will also form a group, and vice versa.

There are two other serious problems that can affect the provenancing of ancient metals by their lead isotope ratios: one is the possibility of addition of lead to the metal (copper, tin, bronze, or silver), and the other is remelting of metal pieces from different locations and making a new artifact from the metal obtained in this way. The addition of lead should be considered if the lead content is above 1–2%. Then the comparisons must be made with the sources of lead or copper/lead ores. The problem of mixing can be assessed by examining the distribution of the data points on the lead isotope plots: each metal obtained from mixing two other sources will plot somewhere along a straight line between the data points representing these other sources.

It is sometimes concluded in the literature that lead isotope provenance methods allow only “rejection” of a source of the ancient metal, and not a positive conclusion of its provenance. This is far too weak an assessment of this provenance tool. The lead isotope compositions, particularly combined with geochemical and archaeometallurgical data, give much more information than a simple rejection of a source on the grounds of difference between lead isotope ratios of ores and the ancient metal. While the lead isotope data do not allow a definite positive assignment, they tell us which assignments are possible, and that this information should be taken further to look at which of the ore deposits can be considered as

sources, particularly if evidence exists that these were exploited at the times in question.

The impact of lead isotope provenance studies in archaeology

Figures 1b and c show an example of a comparative plot of lead isotope ratios for some of the copper ore deposits in the Mediterranean that were exploited in the Bronze Age, and those measured for over 100 ingots of copper of a very specific shape (“oxhide ingots”) dated to the Late Bronze Age and found on various sites in southern Europe, Turkey, and Egypt (Stos-Gale et al. 1997). This plot demonstrates clearly that all analyzed oxhide ingots are consistent with the origin of the ores from Cyprus. This conclusion was at first highly surprising for archaeologists, since many regions where the ingots were found (i.e., Sardinia, Egypt, Greece) exploited their own copper ores in the Late Bronze Age, but chemical and archaeological evidence fully supports this conclusion. The lead isotope research aimed at provenance of Bronze Age metals brought some other unexpected results concerning the exploitation of copper in Europe and import of copper into Scandinavia (e.g., Ling et al. 2014; Artioli et al. 2014; Cattin et al. 2009; Gale et al. 2003).

Strontium as tracer of origin

Strontium (Sr) is a member of the alkaline earths and is known to replace calcium in many minerals. Strontium, therefore, is dispersed in all calcium-bearing minerals, its salts are dissolved in fresh and seawaters, and it is present in sedimentary and igneous rocks. Strontium compounds in the soil and water enter plants, animals and humans through direct uptake or through the food chains. Strontium has four naturally occurring isotopes: ^{88}Sr , ^{87}Sr , ^{86}Sr , and ^{84}Sr , all of which are stable. Their relative abundances are 82.5%, 7%, 9.9% and 0.56% respectively. The isotopic abundances of strontium are variable because of the formation of radiogenic ^{87}Sr through the decay of terrestrial ^{87}Rb with a half-life of 4.88×10^{10} . For this reason, the precise composition

of strontium in a rock or mineral that contains rubidium depends on the age and Rb/Sr ratio of that rock or mineral. Strontium isotopes can be measured very accurately using TIMS and MC-ICP-MS; the typical overall accuracy for TIMS is $\pm 0.01\%$ in measuring the isotopic ratio of $^{87}\text{Sr}/^{86}\text{Sr}$ for about $0.5\text{ }\mu\text{g}$ of Sr extracted from samples of minerals. TIMS has been used for longer than the other instruments and is the most routinely used procedure for strontium isotope analyses. Although using the TIMS is time-consuming (each analysis could take 1–2 h), it requires less strontium compared with other solution-based analyses, and has the highest reproducibility and precision.

Rb/Sr dating is used in geochronology, but the characteristic Sr isotope compositions of minerals from possible sources of raw materials can be used for finding the origin of artifacts made of natural sedimentary rocks, bone, and ivory. The earliest research applying Sr isotopes combined with sulfur to provenancing gypsum used in Mycenaean and Minoan palaces was published in 1988 (Gale et al. 1988).

Isotope ratio analysis of the radiogenic strontium is a well-established procedure used in geology, and therefore a considerable database of Sr isotope ratios in rocks in different locations—regional isoscapes—are available for archaeological projects. $^{87}\text{Sr}/^{86}\text{Sr}$ values change little as they pass from weathered rocks through soils to the food chain, and it has been proven that the isotopic compositions of strontium deposited in human teeth and bones reflect the composition of the natural environment that supplied the food consumed by the individuals. Therefore, analyses of radiogenic strontium isotopes combined with application of other scientific techniques (for example, DNA, as well as oxygen and lead isotopes) in either hard and/or soft tissue allow the reconstruction of ancient human mobility at the individual level. One of the most iconic projects based on this methodology was the study of the remains of the Egtved Girl, in a Bronze Age oak coffin burial in Denmark (Frei et al. 2015).

SEE ALSO: DNA: Mitochondrial; DNA: Next Generation Sequencing; ICP-MS and Material Analysis; Isotopes; Mobility and Lead Isotopes; Mobility and Oxygen Isotopes; Mobility and Strontium Isotopes

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Nuclear Magnetic Resonance (NMR)

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Nuclear magnetic resonance (NMR) is an analytical technique widely used for chemical analysis, materials science, medical imaging, chemical engineering, well logging, process and quality control, and more recently for heritage. This technique is based on the NMR phenomenon, which works by irradiating atomic nuclei with radiofrequency (RF) waves, when the sample is placed in an external magnetic field (Blümich 2000; Callaghan 1991). The magnetic field is usually attained in superconducting magnets and the currently available NMR magnets can have magnetic fields varying between 1 T and 28 T. Superconducting magnets are used both for solution-state and for solid-state NMR, and increased magnetic fields are constantly opening the path to new applications and investigations of more complex systems. In contrast to the superconducting high-field NMR magnets that produce a homogeneous magnetic field, in which the sample is inserted, NMR at low fields can be achieved in inhomogeneous magnetic fields produced by permanent magnets, and in this case the sample can be external to the magnet.

In chemical sciences, NMR is used for determining molecular structures and for gathering information about dynamics in the sample. In materials science and chemical engineering, NMR has been applied for the investigation of a wide range of materials, such as polymers, glasses, zeolites, pharmaceutical polymorphs, energy materials, materials for catalysis and gas storage, superconductors, liquid crystals, food, minerals, and wood. NMR is also a powerful tool for structural biology, where it is applied for studying protein structure and dynamics, protein folding and unfolding, and protein–drug interaction, as well as for the investigation of viruses,

DNA, and RNA. Its contribution to medicine comes under the form of magnetic resonance imaging (MRI), where MRI magnets are utilized both in hospitals and in research centers to study the body by recording three-dimensional images of different anatomical parts such as the brain, spine, and abdomen. MRI scans help with the identification of tumors and can help diagnose various diseases such as cancer, multiple sclerosis, and strokes. NMR is used in well logging for oil reservoir exploration, extracting information regarding rock porosity and pore distribution, rock composition and type, and quality of the fluid—oil, gas, or water. With the development of unilateral low-field NMR sensors, NMR has been increasingly applied to process and quality control. Thus, unilateral NMR is an ideal tool for the nondestructive characterization of materials in industry and it has been applied for the quality control and analysis of rubber products, extracting information on the morphology and domain sizes in semicrystalline polymers and understanding the aging mechanism of polyethylene pipes, and unilateral imaging can be applied for identifying defects in materials. The most relevant application of unilateral NMR in the field of cultural heritage studies is that it is possible to analyze not only portable objects, but also large artifacts or even architectural components directly on site. In the field of heritage, NMR can nondestructively explore historical artifacts, which can lead to understanding the science behind the creation of these treasured items—paintings, frescoes, parchments, historical buildings, musical instruments, ancient mummies, and other artifacts.

NMR is the physical phenomenon that occurs when atomic nuclei that possess a nuclear spin are irradiated by RF pulses while the sample is positioned in a static magnetic field. In the absence of an external magnetic field there is a random distribution of the nuclear spins leading to a null net magnetization, where the net magnetization—or macroscopic magnetization—is represented by the sum of the magnetic fields of each spin. When these nuclear spins are placed in an external magnetic field, they align with the external magnetic

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field, either parallel or antiparallel, where the spins with parallel orientation populate the lower energy levels, while the spins with antiparallel orientation are found on higher energy levels. Resonance occurs when the sample in the static external magnetic field is irradiated with an RF energy corresponding to the energy difference between the two energy levels; the higher the magnetic field, the higher the resonance frequency—for example, at a magnetic field of 9.4 T, the protons resonate at a frequency of 400 MHz, while when increasing the field to 23.5 T, the proton frequency also increases to 1 GHz. The result of RF irradiation is the excitation of the nuclei from the low energy levels to the higher energy levels. This is recorded in NMR experiments under the form of a free induction decay (FID)—the representation of the NMR signal under the time-domain. A Fourier transform (FT) of the FID shifts the representation of the NMR signal from time domain to frequency domain, thus yielding the NMR spectrum.

NMR is a very sensitive tool to local structure, having the advantage of being able to detect the different resonance frequencies of nuclei in different environments, and they are illustrated in a one-dimensional NMR spectrum as peaks on a frequency scale. Depending on the local environment of each nucleus, its NMR corresponding peak can be found at different resonance frequencies in the spectrum, referred to as chemical shifts. Chemical shifts are a very useful tool for structure determination. In one-dimensional spectra, chemical shifts are used to identify the different possible chemical groups in a molecule; however, the larger the molecule, the more crowded the spectrum, which leads to overlap of peaks and difficulties in assigning the spectra. This obstacle is overcome by increasing the number of dimensions in the NMR spectrum and recording multidimensional spectra, which became possible with the invention of two-dimensional correlation NMR spectroscopy (Ernst, Bodenhausen, and Wokaun 1987). Higher-dimensional NMR spectroscopy opens the path to structure determination of larger molecules, including three-dimensional structure determination of proteins, and even full crystal structure determinations when the sample is a powdered solid. While solution-state NMR spectra are characterized by sharp signals,

when investigating solid samples, chemical shift anisotropies and strong dipolar interactions present in these samples broaden the NMR spectra; therefore no chemical shift information can be discerned. In order to achieve high-resolution solid-state NMR spectra, additional techniques have to be applied when working with solid samples. One of these techniques is called magic angle spinning (MAS) and requires the powdered sample to be spun at high spinning speeds in a small cylindrical rotor about a spinning axis oriented at the magic angle (54.74°) with respect to the applied magnetic field. By spinning the sample at the magic angle, the effects of chemical shift anisotropy and dipolar coupling effects are removed (Hennel and Klinowski 2004) and resonances can be more easily resolved.

Other important NMR parameters that one can analyze are the nuclear spin relaxation times (longitudinal and transverse relaxation), J-couplings (through bond interactions), dipolar couplings (through space interactions), quadrupolar parameters, and self-diffusion coefficients.

Certain isotopes of chemical elements possess nuclear spins and, therefore, are NMR “visible”; examples of such isotopes are: ^1H , ^{13}C , ^{15}N , ^{29}Si , ^{31}P , ^{195}Pt , and so on with spin = $\frac{1}{2}$, and ^2H , ^7Li , ^{23}Na , ^{41}K , ^{51}V , ^{235}U , and so on with spin $> \frac{1}{2}$. Over 75 percent of the atomic nuclei that are NMR active possess spin $> \frac{1}{2}$; these are quadrupolar nuclei and they possess a quadrupolar moment arising from a nonspherical distribution of charge in the nucleus of nuclei with spin $> \frac{1}{2}$ (Ashbrook 2009). The natural abundance of various isotopes can range between 0 and 100 percent; thus, while nuclei such as ^1H and ^{31}P have a high natural abundance of 99.98 and 100 percent, respectively, other isotopes such as ^{13}C and ^{15}N have much smaller natural abundance of only 1.11 and 0.37 percent, respectively. The higher the natural abundance, the easier it is to measure certain spins over others. While NMR experiments can be recorded for the low natural abundance nuclei, the measurement time is much longer since the number of spins recorded in the experiment is much smaller. In order to reduce the experimental time there are techniques that allow for NMR measurements to be done on the nuclei with lower natural abundance. The experimental time can be reduced considerably by isotopically

enriching—or labeling—the sample with the desired isotope. A sample can be uniformly or specifically labeled with one or more isotopes. In a uniformly labeled sample, all atoms of a selected chemical element are represented by a single isotope, for example, labeling all the carbon atoms of a molecule with the ^{13}C isotope. When selectively labeling a sample, the labeling is targeted towards specific sites in the molecule, for example, labeling only some of the carbon atoms of a molecule with the ^{13}C isotope, or labeling only certain amino acids of a protein with the ^{15}N isotope. Site-specific labeling is a useful technique when dealing with crowded spectra with many peaks; such is the case of proteins, where hundreds of amino acids give rise to hundreds of overlapping resonances in the NMR spectra. Targeted labeling of certain residues will both simplify the spectra and help assign the resonances corresponding to the labeled amino acids, and therefore help with the structure determination of the protein backbone, which makes isotopic labeling an indispensable tool in biomolecular NMR spectroscopy.

There are ongoing developments in the field of NMR to increase the sensitivity and decrease the experimental time. Different approaches for signal enhancement include dynamic nuclear polarization (DNP) and the use of hyperpolarized gases, such as hyperpolarized ^{129}Xe . Spin manipulations by complex sets of RF pulses to create new pulse sequences that allow for more information to be extracted from the NMR experiments are being developed, and, more recently, the use of magnetic field gradients in combination with complex pulse sequences for a more rapid acquisition of two-dimensional spectra are being exploited to shorten the experimental time. Due to advancements in developing the DNP technique, it is increasingly exploited for applications in both solution-state and solid-state NMR experiments. DNP makes use of the larger polarization of the unpaired electron spins when irradiating a sample with microwaves, and when this polarization is transferred to the surrounding nuclear spins it leads to an enhancement in nuclear polarization, and therefore to an enhancement of the sensitivity of the solid-state NMR experiments by several orders of magnitude (Rosay, Blank, and Engelke 2016). In a similar way, hyperpolarized noble gases can be used in NMR and MRI for experiments at varying magnetic fields—from

the large magnetic fields created in superconducting magnets to very low fields, such as the Earth's magnetic field. The main advantage of using hyperpolarized gases is the large nuclear spin polarization created through spin exchange optical pumping, polarization which can be then transferred to other nuclei, thus enhancing the sensitivity of the NMR experiments. While DNP and hyperpolarization make use of high polarization transfer to the nuclear spins, methods such as ultrafast multidimensional NMR were developed to dramatically reduce the speed of acquisition of multidimensional NMR spectra, resulting in an experimental time of less than one second for a two-dimensional NMR spectrum acquired in only one scan. This method is based on spatial encoding (selective excitations of spins located at different positions in the sample) and makes use of the magnetic field gradient for the acquisition of signal (Freeman 2011). This technique is ideal for the investigation of fast biochemical changes such as protein folding and unfolding, and for the online monitoring of chemical reactions.

In the field of archaeological sciences, different NMR techniques have been applied to study various samples from heritage objects and sites. Solution-state NMR has been applied for the egg yolk identification and aging in mixed paint binding media, while solid-state NMR has been used to analyze a variety of samples relevant to heritage materials—parchments, stone materials from World Heritage sites, amphora residues, ancient wood samples, and so on. However, both solution- and solid-state NMR are invasive techniques, which require the removal of small parts, of the order of milligrams or micrograms, from the investigated object in order to be placed inside the superconducting magnet for the NMR measurements.

A major breakthrough in the application of NMR in heritage studies came with the development of low-field NMR magnets. These instruments are portable unilateral sensors that allow for the in-situ noninvasive investigation of arbitrarily sized objects. These sensors combine open magnets and surface RF coils to excite a sensitive volume inside the object under investigation that is external to the sensor (Eidmann, Blümmer, and Blümich 1996). Examples of portable NMR sensors include the Bruker Profiler[®] and the Profile NMR-MOUSE[®] (MOBILE Universal Surface

Explorer). A challenge arising from the simple magnet design of these portable sensors is the inhomogeneous magnetic field; however, one can use these sensors to probe ^1H longitudinal and transverse relaxation times as well as diffusion times at different depths in the sample, since these parameters are not affected by the magnetic field inhomogeneity. These sensors have two major advantages of high importance for archaeological research—the portability and the noninvasive nature of the technique—enabling scientists to explore a wide range of precious historical artifacts: paintings, frescoes, mosaics, parchments, historical buildings, ancient wood, musical instruments, ancient mummies and bones, and other artifacts (Blümich et al. 2010).

The portable nature of these sensors allows for the NMR measurements to be done on site, at the location where the objects of interest are hosted, such as museums and archaeological sites. Having portable research instruments is essential when conducting scientific investigations at archaeological sites because the object of interest is part of a historical building and cannot be relocated; therefore it needs to be investigated on site. A relevant example is the use of the NMR-MOUSE to map the state of conservation of different frescoes and mosaics from ancient Herculaneum, Italy. Of equal importance is the need to perform the measurements under certain physical conditions crucial to ensure the preservation of the sample during the experiments. This is the case of a study done on Ötzi—the Iceman—a glacier mummy, which is preserved at a constant temperature of -6.12°C and constant humidity of 99.42 percent inside a cold room at the museum in Bolzano, Italy. The NMR-MOUSE is ideal for investigations of Ötzi because the experiments can be performed in the cold room of the museum where the mummy is hosted without the need to relocate the mummy.

The second major advantage of these sensors is their noninvasive nature, and experiments such as relaxation, diffusion, and proton density measurements can be used to characterize heritage in a nondestructive way. This opens the path to studying objects as diverse as paintings, mummies, parchments, and musical instruments, objects that could not be previously investigated by other invasive methods.

A special feature of the Profile NMR-MOUSE sensor is its ability to record experiments at different depths inside the object of interest, by collecting depth profiles, where proton densities can be determined at different depths in the sample with a depth resolution as low as $10\text{ }\mu\text{m}$. This allows for the use of portable NMR to monitor the state of precious heritage objects both at the surface and inside the objects, gaining a more comprehensive understanding of the overall state of conservation of the object.

The large variety of NMR methods available for studying samples under solid-state and solution-state, where experiments can be recorded at a broad spectrum of magnetic fields, ranging from very high fields to low magnetic fields, and even NMR experiments done in the Earth's magnetic field prove that NMR is an outstanding technique with widespread use in multiple areas of science and technology. Of highest importance for the field of archaeology is unilateral portable NMR, a low-field NMR technique that enables a noninvasive characterization of precious heritage objects.

SEE ALSO: Archaeological Sciences; Characterization of Pigments; Chemistry in Archaeology; Conservation; Conservation in Museums; Conservation of Bone, Horn, and Ivory; Conservation of Mosaics; Conservation Science; Deterioration of Mosaics; Isotopes; Magnetic Resonance Imaging (MRI); Paper Analysis

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Optical Spectroscopies

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Optical spectroscopy allows the identification of pigments (see CHARACTERIZATION OF PIGMENTS) such as those found in many paintings, frescoes, and textiles (see TEXTILES), and even the concentration of dissolved absorbing ion species in transparent materials can be determined. For glasses (see GLASS COLOR) and gemstones (see GEMSTONES) optical spectroscopy is well established and is usually used in the transmission mode. In reflectance mode, optical spectroscopy can be applied to semitransparent and opaque materials such as ceramics, glazes (see GLAZES, SLIPS, AND PAINTS), enamels, frescoes, and paintings, as well as dyes (see DYES) in textiles (see TEXTILES) (Tilley 2011).

Optical spectroscopy relies on the fact that certain molecules, ions, and metallic and semiconducting particles can absorb particular energies, that is, specific frequencies of the electromagnetic spectrum. Often, an electron of the valence orbital of a transition metal or rare earth ion is elevated from an energetic ground state to an excited level, which takes a certain amount of energy (EN, in J or eV):

$$EN = h\nu = \frac{hc}{\lambda} = hc\tilde{\nu} \quad (1)$$

where ν is the frequency (s^{-1}), $\tilde{\nu}$ the wavenumber (cm^{-1}), λ the wavelength (nm), h the Plank constant with 6.62×10^{-34} Js, and c the speed of light with 3×10^8 ms^{-1} . Spectra are usually recorded as a function of wavelength (nm), though only the wavenumber gives an energy linear scaling. Thus, when deconvoluting optical spectra with Gaussian bands, it is important to convert wavelengths into wavenumbers.

Figure 1a shows how different electronic configurations for ions in different oxidation states

and coordination split their valence orbitals into states of varying energies. Specific absorption bands are assigned to transitions between particular energy levels, which are named according to the spectroscopic term scheme. The energy between these levels determines the wavelength of the absorption maximum, while the intensity of the transitions depends on the ease of each transition. The transition probability depends on several selection rules, which consider the spin of the electrons and the parity of the wave functions. All d–d transitions are Laporte- or parity-forbidden, which reduces the transition probabilities and subsequently the absorption intensity. This rule is relaxed for noncentrosymmetric geometries, and consequently high intensities arise for absorption bands of tetrahedrally coordinated Co^{2+} ions. The transmission probability is quantified by the molar extinction coefficient ϵ (in $L\ cm^{-1}\ mol^{-1}$), which is listed in Table 1 for typical ions in soda–lime–silicate glasses. Charge-transfer (CT) transitions (see Figure 1b) of an electron from the complexing ligand to the metal cation are Laporte-allowed and as a consequence they have much higher transition probabilities (ϵ of several thousands) (Duffy 1990; Tilley 2011; Möncke et al. 2014).

Many polyvalent ions can have different roles in glass science as either a colorant (see GLASS COLOR) or a opacifier, decolorant, fining agent, or impurity. The ions' valence can resolve the original function of these elements in glasses, while the redox ratio of a polyvalent ion might also hint at production technologies.

Different methods are available for obtaining optical spectra. The abilities and limitations of different instruments from the laboratory to portable equipment, including set-ups working in reflection or transmission mode, are briefly described here. Commercial laboratory instruments work well for glass and ceramic fragments, single mosaic *tesserae*, and other small objects which (1) fit in the sample chamber and (2)

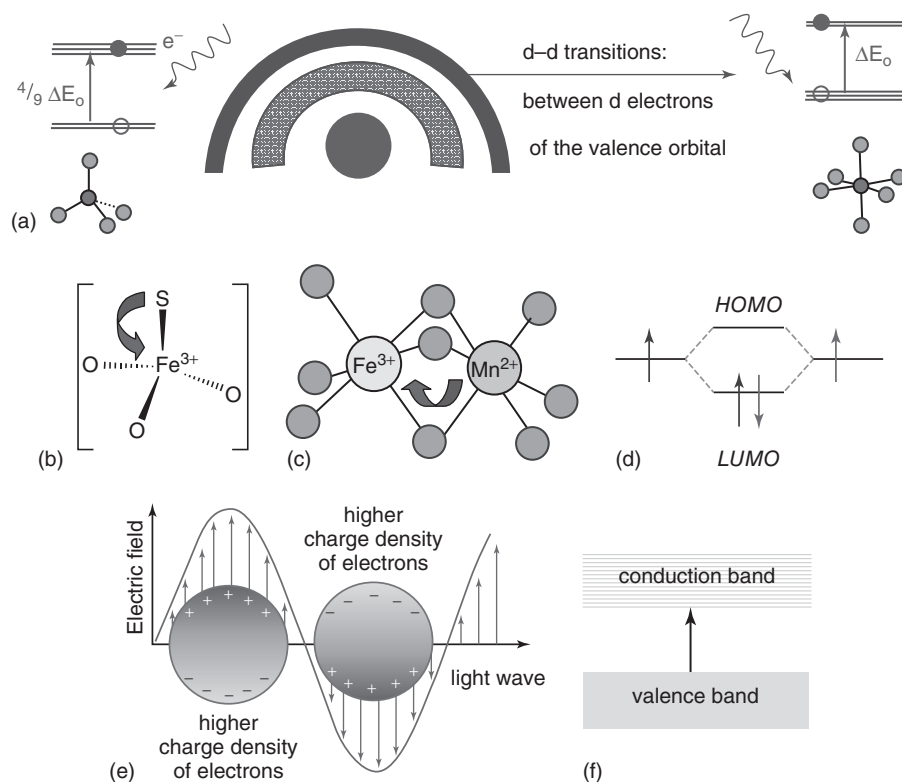


Figure 1 Schematic of different electronic transitions: (a) d–d transitions, typical of dissolved transition metal ions in glasses. Valence and coordination determine orbital splitting (ΔE_o ; octahedral energy splitting) and subsequently absorbed wavelengths and color of material; (b) CT transition from anion to cation in the example of a sulfur–ammonium complex; (c) intervalence CT transition (IV-CT) between two cations of different charge; (d) band scheme of molecular orbital (MO) theory which is often used when discussing organic materials (LUMO, lowest unoccupied molecular orbital; HOMO, highest occupied molecular orbital); (e) schematic of plasmon-resonance; (f) band model, when many energy states are placed very close in energy and the diverse MO bands from (d) or energy levels discussed in (a) merge into energy bands. This depiction applies to semiconductors (including, e.g., CdSe), or when valence and conduction bands overlap, or to metals (including Ag, Au, and Cu nanoparticles).

Source: Panels a–c are reproduced with permission from Möncke et al. (2014). © Elsevier.

can be brought to the laboratory. However, for larger objects, immovable pieces such as church windows, frescoes, and objects from valuable collections, portable spectrometers are an alternative option.

In transmission mode, spectra can be evaluated qualitatively, identifying absorbing ions, but also quantitatively for the colorants' concentration. The transmittance T is usually given as the ratio of the intensity of the probe beam passing through the instrument path without a sample

I_o , relative to the intensity of the corresponding beam passing through the sample I_t :

$$T = \frac{I_t}{I_o} \quad (2)$$

For most commercial spectrometers, the measured wavelength range extends from 200 up to 3,000 nm. Transmission spectra are usually transformed into absorbance spectra for evaluation. Commercial instruments use the decadic logarithm when converting T to

Table 1 Typical colorants and their transition probability in soda–lime–silicate glasses.

<i>Ion</i>	<i>Main transition(s) in visible</i>	<i>CN</i>	λ_{max} (nm)	ϵ (L cm ⁻¹ mol ⁻¹)	<i>Color</i>
Cu ⁺	d^{10}				Colorless
Cu ²⁺	d^9 ² E _g (D) → ² T _{2g} (D) tetragonal distorted	O _h	~800	~25	Sky blue
Co ²⁺	d^7 ⁴ A ₂ (F) → ⁴ T ₁ (P) split triplet	T _d	650 600 540	~180–200	Deep blue
Mn ³⁺	d^4 ⁵ E _g (D) → ⁵ T _{2g} (D) tetragonal distortion	O _h	480	~135	Deep purple
Mn ²⁺	d^5 ⁶ A ₁ (S) → ⁴ A ₁ (D)/ ⁴ E(D)	T _d	420	~0.3	Light orange
Fe ²⁺	d^6 ⁵ T _{2g} (D) → ⁵ E _g (D) tetragonal distorted	O _h	1050	~30–54	Light blue
Fe ³⁺	d^5 ⁵ E(D) → ⁵ T ₂ (D) ⁶ A ₁ (S) → ⁴ T ₁ (G), ⁴ T ₂ , ⁴ A ₁ / ⁴ E	T _d T _d /O _h	2000 380, 435, 555	~3–5	Yellow
Fe ³⁺ -O CT			210	~2500	Yellow
Fe ²⁺ -O CT			250	~5000	
Fe ³⁺ -S CT			410	~9000	Yellow to brown

absorbance A , though the natural logarithm is used when converting infrared (IR) spectra (see INFRARED REFLECTANCE SPECTROSCOPY) or when determining the band gap energy (Tilley 2011). Thus, it is always helpful to state the used modulus.

$$A_\lambda = \log \left(\frac{I_t}{I_0} \right)_\lambda \quad (3)$$

Absorbance is given in dimensionless units of absorbance. Optical density OD is the absorption normalized to a 1-cm-thick sample; thus OD is given in cm⁻¹. Though this term is out-of-date, it is helpful to normalize spectra to a defined sample thickness, since the coloring intensity depends on the probe beam's path through the sample. It is generally beneficial to mention the sample thickness.

UV-Vis-NIR spectrometers measure absorbance units of up to 2–3. New equipment might even reach absorption values of up to 10, providing that homogenous, plane parallel sample plates with optical grade polishing and 1 cm² or more dimensions are measured. Fiber optics allows analysis of much larger samples.

It is important to realize that the measured absorbance, or more precisely the attenuation

(ATT), is the sum of many different effects, such as the absorption of energy due to electronic or vibrational transitions A , reflection R , or scattering S .

$$ATT(\lambda) = A(\lambda) + R(\lambda) + S(\lambda) = 1 + E(\lambda) \quad (4)$$

E denotes the emission of radiation, for example from fluorescing ions. If emission is present, it adds photons to the measured light beam, and consequently, the analyzed transmitted light of some wavelengths might be higher in intensity than the intensity of the probe beam. The different effects are schematically depicted in Figure 2.

Especially when handling archaeological samples with inclusions, corrosion layers, or scratched surfaces, scattering will be significant. This is often reflected in an increased background absorption, which is often especially enhanced in the UV-Vis region.

Quantification of absorbing species is based on Beer–Lambert's law:

$$A = c d \epsilon \quad (5)$$

with the concentration of the coloring ion c (mol L⁻¹), sample thickness d (cm), and molar

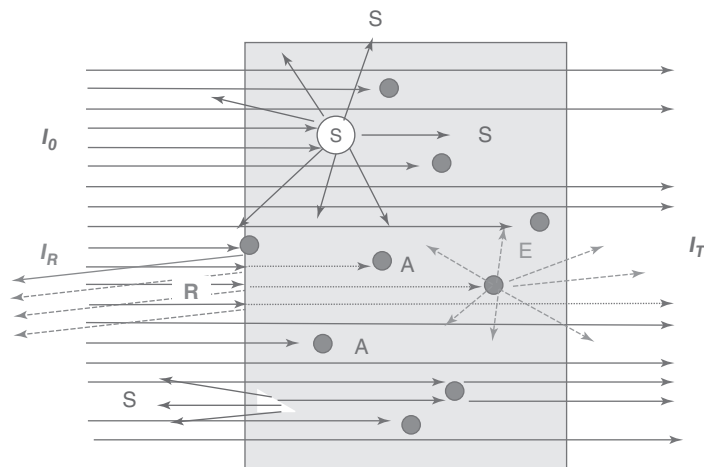


Figure 2 Schematic of absorbing (A), scattering (S), reflecting (R), and emitting (E) centers or surfaces in a transparent material such as glass.

extinction coefficient ε ($\text{L cm}^{-1} \text{ mol}^{-1}$). This way of quantifying ion species is particularly important since typical techniques for the quantitative chemical analysis of glasses, such as inductively coupled plasma mass spectrometry (ICP-MS) (see ICP-MS AND MATERIAL ANALYSIS), X-ray fluorescence (XRF) (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)), and scanning electron microscopy energy dispersive X-ray spectroscopy (SEM-EDS) (see SEM-EDS AND MATERIAL ANALYSIS), only give the total element fraction but no information on the ions valence.

For quantification, only the absorption component of equation (4) is considered. For well-polished, homogenous transparent and plane parallel samples such as glasses (see GLASS COLOR), scattering can be neglected and reflectance can be accounted for by subtracting a calculated reflectivity value, based on the refractive index (Tilley 2011) with $n_{\text{air}} = 1$:

$$\text{with } R = \frac{(n_g - 1)^2}{(n_g + 1)^2} \quad (6)$$

For soda–lime–silicate glasses and air, the refractive index is $n_g \approx 1.5$, accounting for an average transmission loss due to reflectance of $R = 3\text{--}4$ percent.

For irregular sample geometries, the transmitted light will be refracted in different directions on the inner and outer surface instead of passing

straight through the sample. In this case, collecting all transmitted light beams requires the use of an integration sphere.

For very large or opaque samples, measurements are better obtained in the reflectance mode. Reflectance spectroscopy measures the reflectivity R , defined as the ratio of the intensity of the reference beam I_0 over the intensity of a fully reflected beam I_R :

$$R = \frac{I_R}{I_0}. \quad (7)$$

Only light wavelengths that are not absorbed are reflected from the sample. A pure white background such as polytetrafluorethylene (PTFE) or BaSO_4 is used for measuring the reference beam intensity I_0 .

Reflectance can be recorded either in direct or in diffuse mode. Whereas the direct mode only collects beams reflected at normal incident, the diffuse mode uses an integration sphere, collecting all reflected light beams, and therefore the sensitivity is generally higher when using a sphere.

Since the sample thickness is not probed, quantification can only be attempted semi-quantitatively through comparison with similar reference materials of known colorant concentration. Qualitatively, the same results can be obtained as in transmission spectroscopy. Any absorbing species can be identified and redox ratios of dissolved ions might be estimated from the relative band intensities.

Fiber optics reflectance spectroscopy (FORS) is an important variation employed in art and archaeometry (see *ARCHAEOLOGY*), since portable set-ups allow noninvasive in-situ measurements of very large objects (e.g., church windows, paintings, frescoes) or of precious museum pieces. FORS is an established technique for the identification of pigments (Aceto et al. 2014) and is increasingly used for glasses (see *GLASS COLOR*), glazes (see *GLAZES, SLIPS, AND PAINTS*) and enamels (Maltoni and Silvestri 2016).

The set-up of portable instruments is generally the same as described earlier, only that the light is passed through fiber optics between the sample and monochromator or detector, respectively. Measurements in transmission mode can also be realized if both sides of a large vase or large glass pane are accessible within the given length of the optical fibers.

The cost of such a set-up varies considerably between homemade and commercial laboratory equipment. Assembling a FORS set-up is relatively easy since only few components are required: a light source, spectrometer, and two optical fibers, one to illuminate the sample and the other to collect the diffused light. Equipment costs will be higher if the system's wavelength range is extended below 360 nm in UV or above 1000 nm in NIR.

Sensitivity is always lower in portable devices working with fiber optics compared to fully enclosed laboratory equipment, since any scattered light from the environment will negatively affect optical measurements. Enfolding the sample and FORS optical fiber heads by black velvet curtains helps to reduce light contamination.

Colors can be objectively described by various parameters, also called color space. This might be useful for publications or exhibition catalogs, like the visual comparison with reference materials such as Munsell or Pantone color cards. $L^*a^*b^*$ is a device-independent method, based on the CIE 1976 representation, which includes other typical gamuts, such as, for example, the RGB color model which is mostly used in computer screens (Tilley 2011). In the $L^* a^* b^*$ representation, L^* is the lightness, with $L^* = 0$ for the darkest black and $L^* = 100$ for the brightest white; a^* (+ red / - green) and b^* (+ yellow / - blue) are color channels. True neutral gray values are

found at $a^* = 0$ and $b^* = 0$. While $L^* a^* b^*$ values can be calculated from transmission spectra, direct measurements of transparent samples pose problems, since the sample thickness determines the perceived color.

Spectra of typical transition metal ions in glass (see *GLASS COLOR*) can be found in that entry, and in the literature (Möncke et al. 2014). Similar absorption bands are often found in crystalline pigments and gemstones (Fritsch and Rossmann 1987, 1988). A deep yellow to brown color in glasses can be caused by the intervalence-CT transition, from $S \rightarrow Fe^{III}$ in $[FeO_3S]^-$. The blue color in lapis lazuli is due to an interanion-CT transition in S_3^- .

Several databases are available for pigment identification. Spectral features such as the characteristic absorbing wavelengths and relative band intensities of the measured spectrum of unknown samples can be compared with well-known spectra. The online database of FORS spectra (<http://fors.ifac.cnr.it/index.php>) offers a high number of references of pure pigments. These spectra are not downloadable, whereas the spectra from the FORS Spectral Database of Historical Pigments in Different Binders (Cosentino 2014) can be downloaded as csv files. When analyzing paintings, many organic binders will contribute with the absorption of their complex organic molecules to the overall spectrum. Both listed databases account for this by the inclusion of spectra from the same pigments mixed with different binders (see *PIGMENTS AND BINDERS*).

Organic pigments are more often used in textiles (see *TEXTILES*) and manuscripts; see also ink (see *INK*) (Aceto et al. 2014). Electronic transitions of complex large organic molecules are best described by the molecular orbital theory. Here, not only individual bonds between atoms but also all valence electrons are depicted in combined molecular orbitals, influenced by the combination of all the molecule nuclei. Such electronic transitions between the LUMO and HOMO are depicted in Figure 1d. Especially molecules with a large number of conjugated double bonds will absorb in the visible wavelength range; see also organic dyes (see *DYES*) such as indigo (Tilley 2011).

Cut-off glasses contain inorganic crystalline pigments and are colored by "cutting off" the blue spectral region. The wavelength of the cut-off

depends on the number and size of the crystals. When only the blue spectral region is cut-off the glass appears yellow. When the green is cut-off in addition to the blue, the glass appears orange to red. When the cut-off is shifted further, the glass appears brown and finally black. The absorption is linked to the electronic transitions of electrons between the valence and conduction bands of semiconductor-type crystallites (Figure 1f) (Duffy 1990; Tilley 2011). For such transitions, a minimal radius of only 1.3 nm is required and the band gap shifts with increasing crystallite radius into the visible wavelength region.

Plasmon-resonance absorption of metallic nanoparticles gives silver stained glasses their yellow color, and gold and copper ruby glasses their red color. In metals, positive metal nuclei are embedded in a cloud of negatively charged electrons. When the diameter of the particles is large enough (10–100 nm), these free electrons can be excited in collective oscillations by a beam of irradiation. At the resonance condition, photons of the corresponding energy are absorbed by these nanoparticles (Figure 1e). The absorption by plasmon-resonance depends on the alloys' composition, as well as on the size and shape of the nanoparticles. Scattering effects can be neglected for small particles of less than 50–60 nm in diameter (Tilley 2011).

Mie calculations allow for the simulation of a measured reflectance spectra when the refractive index of the glass matrix and the metal are known. From such calculations, the particle size distribution can be estimated (Tilley 2011). In contrast, opaqueness and opalescence are introduced by scattering particles of larger dimensions. Glasses containing particles (with a diameter d) show opacification by refraction and reflection ($d > \lambda$), by diffraction ($d \approx \lambda$), or by opalescence ($d < \lambda$). Opalescence glasses are often dichroic. Blue, short wavelengths scatter about ten times stronger than the longer red wavelengths. In reflectance, we see the scattered blue light on the glass surface, while the blue is filtered out in transmission and only the red wavelengths transverse through the sample.

The Lycurgus Cup is perhaps the most well-known example of dichroic glass and appears yellowish-red when looking through it and opaque greenish-yellow when looking upon it. The observed attenuation is the sum of scattering by the particles and absorption by

plasmon-resonance; both factors show dissimilar wavelength dependence and, in combination, different colors are observed when the cup is viewed in either reflectance or transmission (Tilley 2011).

For elastic light scattering phenomena, photons interact with matter through a change in direction, but without a change in energy. In the case of inelastic light scattering, both the energy and the direction of the photon are modified. Important examples are Raman scattering and luminescence. Both effects are used extensively in archaeometry (see *ARCHAEOMETRY*). Raman spectroscopy allows the identification of inorganic pigments, while surface-enhanced Raman spectroscopy is employed in conservation (see *RAMAN SPECTROSCOPY IN CONSERVATION*) and on textiles (Ricci et al. 2016). Raman and the complementary method of IR spectroscopy—see also IR absorption (see *INFRARED ABSORPTION SPECTROSCOPY* (IR, FTIR, DRIFT, ATR)) and IR reflectance (see *INFRARED REFLECTANCE SPECTROSCOPY*) spectroscopy—both analyze vibrational modes with energies in the IR wavelength range.

Luminescence is the emission of light after excitation (Tilley 2011). Most common is excitation by photons—see also photoluminescence of Egyptian blue (see *PHOTOLUMINESCENCE OF EGYPTIAN BLUE*) or dating by optically stimulated luminescence (see *DATING AND OPTICALLY STIMULATED LUMINESCENCE*) and optically stimulated luminescence (see *OPTICALLY STIMULATED LUMINESCENCE*). Many polymers such as polyacryl-based glue used in conservation and synthetic paints will show distinct emission spectra. Luminescence can also be triggered by thermal energy—see also dating of ceramics by thermoluminescence (see *DATING CERAMICS AND LUMINESCENCE*) and thermoluminescence (see *THERMOLUMINESCENCE*)—or by IR phonons—see also dating by IR-stimulated luminescence (see *DATING AND INFRARED STIMULATED LUMINESCENCE*).

SEE ALSO: Databases in Archaeology; Dyes; Gemstones; Glass and Faience; Glass Color; Glazes, Slips, and Paints; Ink; Optically Stimulated Luminescence; Photoluminescence of Egyptian Blue; Pigments and Binders; Spectroscopy; Textiles

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Optically Stimulated Luminescence

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Since the invention of radiocarbon dating in the 1950s, the arsenal of science-based dating methods has been populated by novel methodologies, pushing our understanding of human evolution further back in time. Science-based dating methods (see *DATING IN ARCHAEOLOGY*) in archaeology take advantage of natural “chronometers” which can be reset by certain biologic, anthropogenic, or other environmental events (Aitken 1998). For example, the radioactive decay of ^{14}C in dead organisms and the progressive racemization of amino acids in collagen are thought of as natural “clocks.”

Among them, luminescence dating methods (i.e., optically stimulated luminescence (OSL) dating (see *DATING AND OPTICALLY STIMULATED LUMINESCENCE*) and its forerunner thermoluminescence (TL) (see *THERMOLUMINESCENCE*)) are of great value in archaeology and the earth sciences. Given that radiocarbon (^{14}C) dating is limited to organic materials no older than 50 kya (Aitken 1998), on the one hand, and the ubiquity of silicate clasts, on the other hand, OSL dating and its long-range dating alternatives is nonpareil.

Luminescence techniques make use of the emission of light from minerals that have been exposed to natural ionizing radiation when undergoing stimulation. When stimulation is carried out by shining light, the light emitted in response is called optically stimulated luminescence (OSL). If stimulation involves heating the sample at high temperatures the emitted light is called thermoluminescence (TL). OSL dating was introduced by Huntley, Godfrey-Smith, and Thewalt (1985). Because OSL is more sensitive to light than TL, OSL is suitable for dating the last exposure of mineral grains to sunlight, known as the *bleaching* event, which corresponds to

the time of deposition. This necessity is met for sediments from archaeological layers.

Grains of minerals that are abundant in sediments, such as quartz and feldspar, memorize their exposure to ionizing radiation: The longer the exposure, the stronger their OSL signal. Natural ionizing radiation is expressed as radioactivity, emitted from decaying isotopes (see *ISOTOPES*) (U, Th, and K) which are ubiquitous in sedimentary environments, and cosmic radiation impinging the Earth's surface from all directions.

Generation of luminescence is associated with the presence of defects in the mineral structure, known as *traps*. In sedimentary deposits the mineral grains are locked from the sunlight, and the intrinsic electronic charge excited by the ionizing radiation may be captured in the traps. Trapped charge accumulates through geological time. In the laboratory under safe lighting conditions (dimmed red light), the accumulated charge can be artificially evicted by stimulating the minerals with special light sources (blue LEDs, for example), and the eviction of trapped electrons will be accompanied by the release of a stream of photons which corresponds to OSL.

The intensity of the OSL signal is dependent on the amount of ionizing radiation the minerals were exposed to, and is measured in *Grays* (Gy). If the dose is divided by the rate at which the dose was delivered (Gy/kya), the time elapsed since the last bleaching event can be estimated. The latter corresponds to the *luminescence age*.

$$\text{Age (kya)} = \frac{\text{Equivalent dose (Gy)}}{\text{Dose rate (Gykya)}} .$$

Sample collection for OSL dating involves the introduction of light-tight (aluminum, PVC) tubes into an excavated (or natural) profile. Sampling is usually carried out in the range of 300–700 g, depending on the nature of the sediment. In cases where the sediment is consolidated, making it difficult to penetrate tubes, we usually extract a block of rock which is then wrapped in opaque wrapper. In cases where the above is impractical, the sample can be excavated

either in daylight under coverage of an opaque tarpaulin and using a dim red light or at night holding a red-light torch and then putting the sample in an opaque bag.

In the laboratory, several separate stages of chemical treatment aim at isolating suitable minerals, such as quartz and feldspar. Sample preparation must be performed in a “dark room,” under red light of low intensity. Initially, the material is processed with hydrochloric acid (HCl) to remove carbonate minerals and calcite cements, and then it goes through hydrogen peroxide (H_2O_2) to get rid of the organic materials. The remaining material is passed through a set of sieves to isolate sand-sized fractions, which typically range between 90 and 180 microns. For sand-sized grains, quartz and feldspar can be separated on the basis of density using heavy liquids: At a heavy-liquid density of 2.62 g cm^{-3} , feldspar floats while quartz sinks to the bottom of a test tube. The mineralogical fractions are then separately etched by hydrofluoric acid (HF) in order to eliminate the outer rind which is nonuniformly irradiated in nature. A final treatment with HCl

is important to remove fluorides during the etching stage. Purified grains are then mounted on approximately 10-mm-diameter stainless-steel or aluminum discs with silicon-spray and are ready for measurement. See Figure 1.

Luminescence readers are instruments designed to conduct signal recordings, heating, artificial irradiations, and OSL stimulations with various light sources: blue diodes, infrared (IR) diodes, green diodes, or IR lasers. Quartz’s luminescence is typically stimulated with blue (470 nm), whereas feldspar is stimulated by IR (870 nm) light. In the case of feldspar, the released luminescence is termed infrared stimulated luminescence (IRSL). Among the two, quartz is considered more appropriate than feldspar, as the latter may suffer from a phenomenon called anomalous fading, which results in age underestimation. The emitted luminescence is detected by a sophisticated unit including a photomultiplier tube and specific detection filters. Artificial irradiations are carried out by a beta-source ($^{90}\text{Sr}/^{90}\text{Y}$) which is attached to the reader and placed in a special protective shielding. The reader

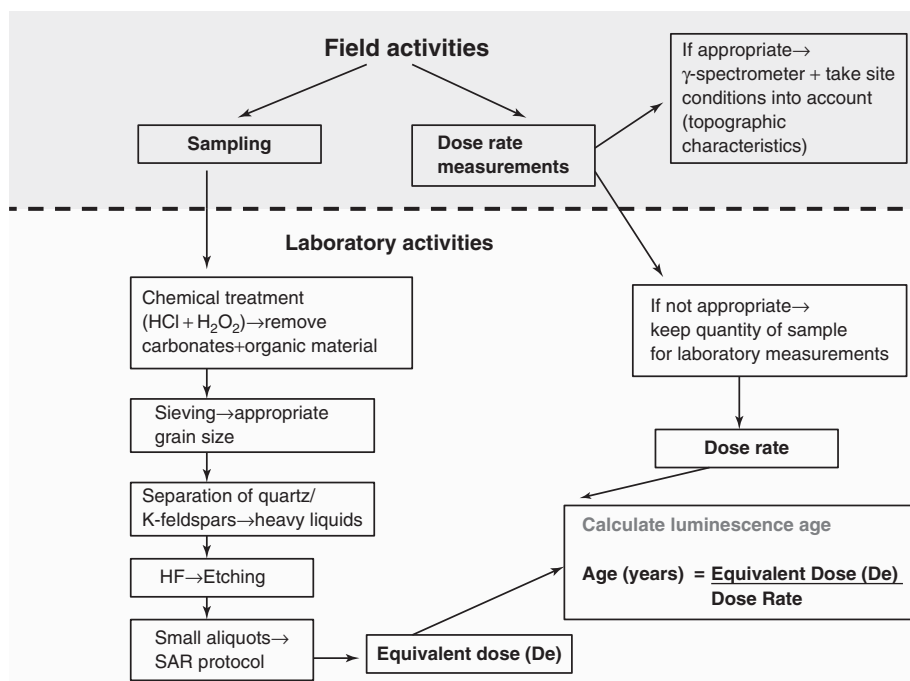


Figure 1 Flowchart showing appropriate procedures for equivalent dose and dose rate determinations to calculate luminescence date.

is automatic and entirely computer-controlled. It can be programmed to execute a sequence of treatments and measurements at the user's will.

Estimation of the natural dose involves the measurement of the natural OSL signal and then its regeneration with successively higher known (regenerated) doses. The OSL signals measured in response (including the natural one) are normalized to the signal of a constant dose (test dose). The resulting plot associating all pairs of dose and OSL signal is called the growth curve, and extrapolation of the normalized signal onto the growth curve defines the laboratory equivalent of the dose termed the *equivalent dose* (D_e) (Figure 2). The above method of D_e evaluation is known as the single aliquot regenerated (SAR) dose protocol (Murray and Wintle 2000). This protocol has the advantage that it enables multiple measurements on individual subsamples (aliquots), allowing the monitoring of the fluctuation of D_e in the sample.

Calculation of the *dose rate* includes the determination of radioisotopes, either by conventional analytical methods, such as neutron activation analysis, or by ICPMS, or techniques based on the release of α -, β -, and γ -rays from the decaying nuclei, such as alpha- and beta-particle counting, or gamma spectroscopy. Radioisotope concentrations are then transformed to dose-rate

units ($\text{Gy} \cdot \text{ka}^{-1}$) which provide the dose rate per radioisotope concentration (ppm).

Accuracy in OSL dating is a serious problem and is case-dependent. Typically, anything less than 10 percent is acceptable. The precision of the average D_e on samples consisting of multiple grains with different burial histories and bleaching is problematic. That is why geochronologists often turn to single grains to acquire better resolution. The oldest age limit of OSL dating is managed by the concentration of luminescence and is defined by the local dose rate, restricting the technique to less than approximately 200 kya. Several methodological and technological developments can extend the age limits further into the Pleistocene (Arnold et al. 2015).

Apart from sediment dating, OSL can also date architectural structures. This can be done by calculating the time passed since the last exposure of a stone's surface to daylight. OSL dating of architectural remains is based on the hypothesis that stone surfaces would receive enough daylight before they were erected. If a sufficient amount of quartz grains can be extracted, then conventional OSL dating protocols could be employed to date the monument.

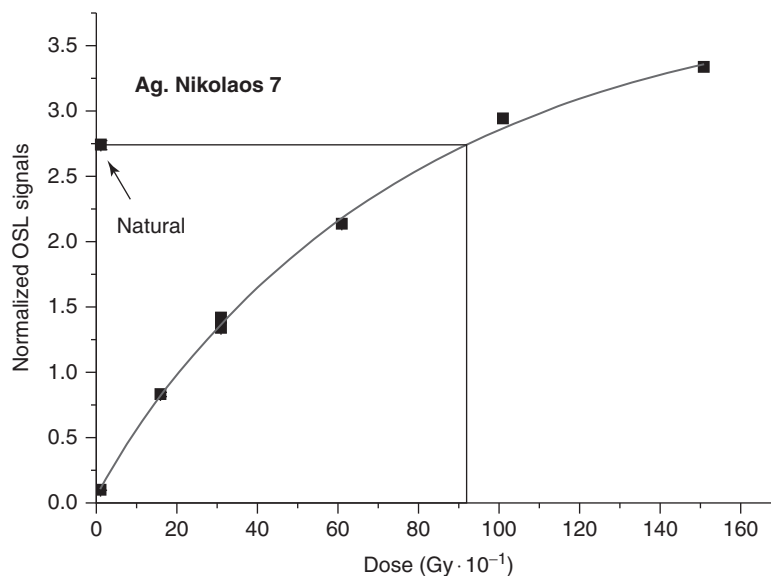


Figure 2 Growth curve of fluvial quartz from northeast Crete, Greece.

Case studies

Dating archaeological structures

OSL was applied to date extensive prehistoric stone structures in the Black Desert of Jordan in the northern Arabian Desert. When seen from above, these structures appear as geometric lines, which are locally known as the “Works of the Old Men” (Athanasas et al. 2015). Despite their large extent, nothing was known of their chronology. These structures are the result of long-term alteration processes of the desert by the prehistoric inhabitants that resulted in the characteristic landscape of the “Works,” an issue of cooperative work with functional and religious importance. OSL dating was successful in resolving the enigmatic chronology of these structures, showing they were created by a prehistoric culture during the period 8.55–5.42 kya (Late Neolithic–Early Bronze Age).

Dating archaeological sites

OSL was applied to the Middle Paleolithic Blombos Cave in South Africa, with the aim of determining phases of human installation (Jacobs, Wintle, and Duller 2003). The deposits contained significant artifacts, including pieces of engraved ochre, a large number of worked lithics, and bone tools. It has long been known that the majority of the Middle Stone Age (MSA) in South Africa extends beyond the range of radiocarbon dating (~50 kya); therefore, the application of alternative chronological methods, such as OSL dating, was deemed necessary. The ages for the archaeological sediments were obtained from single-grain measurements. An age of 143.2 ± 5.5 kya for the lowermost wind-blown sand deposit of the MSA sequence pointed at oxygen isotope stage (OIS) 6, when the sea level was at about 120 m below the modern sea level. The earliest MSA archaeological phase was found to contain teeth of anatomically modern humans, but most importantly fragments of artistically engraved ochre. This layer was dated to 98.9 ± 4.5 kya, coinciding with the sea level during oxygen isotope substage 5c. The OSL chronology for Blombos Cave not only showed that early human occupation at the site was controlled by global changes in sea level but also demonstrated the earliest known evidence of art.

Dating the paleogeography of archaeological sites

Theodorakopoulou et al. (2012) studied the depositional environment of Istron archaeological site in northeastern Crete, Greece and its sedimentological response to Holocene climatic events. The results of a multidisciplinary geoarchaeological research undertaken in the coastal area of Istron provided information on the depositional environment and the paleoenvironmental and paleogeographic evolution of the area during the Holocene. The identification of the stratigraphy and the distinction of sedimentological units, along with changes of sedimentation rate determined by OSL dating, provided evidence of landscape evolution. Their research also determined the influence of climatic events on the development of archaeological settlement patterns.

SEE ALSO: Archaeological Sciences; Dating Ceramics and Luminescence; Dating Rock and Desert Varnish

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Raman Spectroscopy

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Introduction

Archaeological materials provide a unique source of knowledge about human societies in the past, the uses of raw materials, the technology and manufacturing techniques of artifacts, exchange routes and trade, and materials deterioration. It is very important to apply a suitable set and sequence of techniques for characterization of materials, including noninvasive methods such as spectroscopic techniques for in-situ and laboratory analyses, and, depending on the archaeological questions and the kind of studied material, to complete the examination of samples by microanalysis using electron microscopy techniques, molecular and atomic spectroscopies, and chromatography.

Raman is a relatively recent technique for issues related to heritage objects. It has been applied first to the identification of pigments, and its application has been extended to most of the materials of the archaeological record (Edwards and Vandenabeele 2016).

The technique is based on the characteristic energy dispersion of a laser beam after light interaction with the molecules of the material. As a result, a specific spectrum of the material is obtained. Identification of the material can be carried out by comparison with extensive databases of spectra of reference materials and compounds. Depending on the material composition, more than one laser beam is required. The Raman technique is very specific, and can provide chemical and structural information from the same spectrum.

However, some limitations exist due to the low sensibility of the technique and high fluorescence background due to laser interaction with the material. Another important limitation is

the beam damage due to deposited energy at the surface, so the beam intensity must be kept as low as possible, but high enough to obtain a suitable spectrum. This problem depends on each case. To overcome these difficulties, special methods of Raman, such as surface-enhanced Raman spectroscopy (SERS), have been developed, mainly for sample analysis in the laboratory.

Raman instrumentation can be used in the laboratory for microanalysis or in the field using portable equipment for punctual analysis or even surface mapping of objects. This spectroscopy can be successfully applied to inorganic and organic materials and objects from the archaeological record: pigments and paintings, pottery, stone artifacts, gems, glaze, glass, and bone remains.

The Raman effect

The Raman effect has its origin in the electronic polarization of the molecules due to ultraviolet, visible, and near infrared light (Nakamoto 2009). It was reported for the first time in 1928 from the inelastic dispersion of light through a fluid (Raman and Krishnan 1928).

Two processes can occur as a consequence of the light scattering of the molecules. The most likely, the Rayleigh effect, takes place when the scattered photon energy is the same as the incident one. In the second case, the Raman effect, the energy of the scattered photon differs from the incident photon energy. The shift in energy is responsible for the Raman spectra of the molecules. The Raman effect is around one hundred times less probable than the Rayleigh effect.

The vibrational energy levels of a molecule are $E_n = h(n + \frac{1}{2})\nu$, where $n = 0, 1, 2, \dots$; h is the Plank constant; and ν is the frequency of the vibration. When the vibrational transition of the molecule occurs from the ground state ($n = 0$) to the next one ($n = 1$), the energy of the scattered photon is lower than the incident one; this process is known as the Raman Stokes effect. In contrast, the energy of the photon scattered in

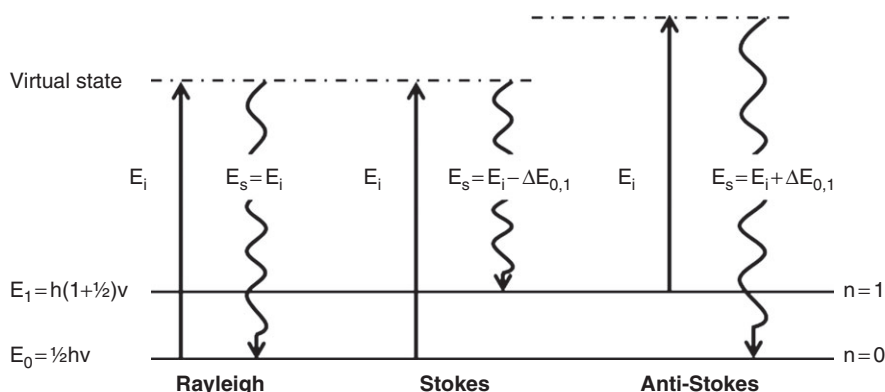


Figure 1 Rayleigh scattering: the energy of the scattered photon is equal to the incident one; $E_s = E_i$. Raman Stokes scattering: the energy of the scattered photon is lower than the incident one; $E_s = E_i - \Delta E_{0,1}$. Raman anti-Stokes scattering: the energy of the scattered photon is higher than the incident one; $E_s = E_i + \Delta E_{0,1}$. $\Delta E_{0,1}$ is the difference of the energy between levels $n = 1$ and $n = 0$.

the Raman anti-Stokes effect is higher than the incident photon one (Figure 1).

When a molecule is placed on an external electronic field E , a dipolar moment is induced according to:

$$p = \alpha E \quad (1)$$

where α is the bound polarizability, that is, a measurement of the electronic cloud deformation due to the incident radiation. If the electronic field is regarded as a plane wave, it can be demonstrated that the polarizability takes the form:

$$p = p(\nu_{\text{ext}}) + p(\nu_{\text{ext}} - \nu_v) + p(\nu_{\text{ext}} + \nu_v) \quad (2)$$

where ν_{ext} is the frequency of the incident radiation, and ν_v is the vibrational frequency of the molecule. The first term in equation (2) is the Rayleigh scattering contribution of the polarizability; the second and third are the Raman Stokes and Raman anti-Stokes terms, respectively (Vandenabeele 2013).

According to the Maxwell-Boltzmann distribution, at room temperature, the probability of observing the Raman Stokes effect is higher than the Raman anti-Stokes effect, because the majority of the molecules are in the ground state E_0 .

Instrumentation

A Raman spectrometer consists of a laser source, a system for sample illumination, a device

with a suitable spectral analyzer—which has to be able to disperse all the light according to its wavelength; it could be a monochromator (dispersive instrument) or an interferometer (Fourier transform instrument)—and the detector. The light scattered by the sample reaches the Rayleigh filter (Figure 2) where all the Rayleigh radiation is eliminated using “holographic notch” and dielectric band filters. Raman scattering light passes through a grating which divides the light into its components. The periodic variation of the grating allows it to obtain the spatial resolution of the light according to its wavelength. In the detection, photodiode arrays or charge-coupled devices (CCDs) are often used and each pixel records a different spectral band. A multichannel device is utilized in order to scan the complete spectral range (Larkin 2011). Most common laser wavelengths are 532 and 785 nm; however, 514, 633, and 1064 nm are also utilized. Laser beam spot usually ranges from 1 to 50 μm depending on the system optics; thus, Raman spectroscopy is considered a microanalytical technique.

Recent developments in systems using laser scanners and automatic plates have allowed mapping of the composition of a region of the sample surface or even objects. Also, confocal devices provide a three-dimensional distribution of the compounds of the materials at the surface.

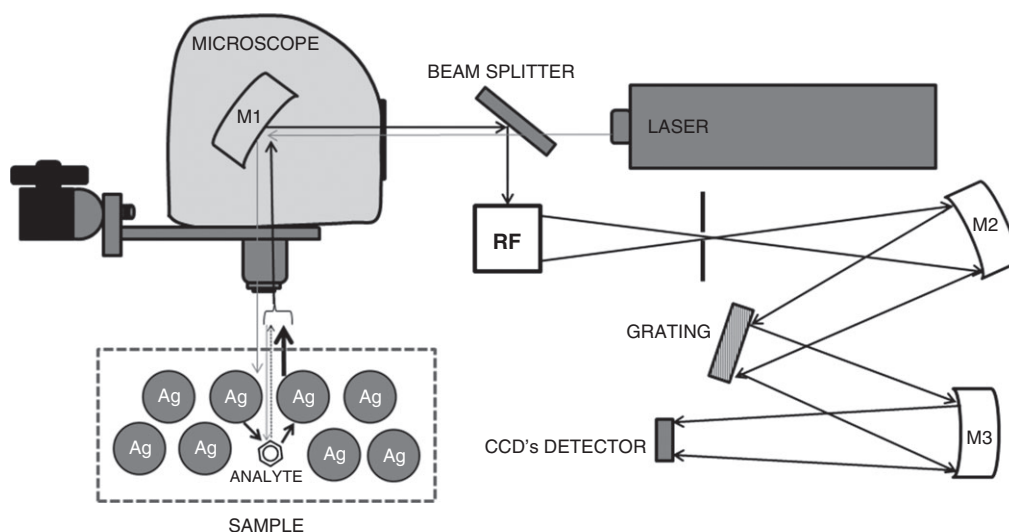


Figure 2 A simple Raman dispersive setup (180° geometry). The microscope permits focusing on the sample surface and directs the scattered light to the spectrometer. M1, M2, and M3 are mirrors and RF is the Rayleigh filter. With SERS enhancement (sample detail (dashed line), laser beam (gray lines)) is amplified by a nanostructure molecule (black line) and reaches the analyte. Raman scattered light of the analyte is amplified repeatedly by other nanostructures (wide black line).

Surface-enhanced Raman spectroscopy (SERS)

Often, the Raman effect is accompanied by a fluorescence interference which hinders the observation of Raman bands in spectra. Fluorescence is the emission of light caused by the relaxation process of a molecule. Another way in which the molecule can lose energy is through the nonradiative process: When a molecule absorbs light, the extra energy is released as thermal energy which is transmitted to the environment.

Success with Raman spectroscopy depends on the material studied. In practice, compounds that contain aromatic rings emit strong fluorescence, such as carbonyl, aliphatic, and alicyclic compounds, and conjugated double-bound structures. For this reason, organic compounds are difficult to be studied by Raman spectroscopy. Nevertheless, many techniques have been developed in order to eliminate the fluorescence background. One of them is SERS, a technique where the Raman signal is amplified and the fluorescence is quenched by the metal nanostructures that are placed very close (some nanometers) to the studied molecule (Aroca 2006). Amplification

of the Raman signal (up to several orders of magnitude) can be explained by two processes: an electromagnetic and a chemical mechanism.

When a metal nanoparticle is radiated with light of a certain wavelength, electrons on the surface begin to oscillate in a collective way in phase with the incident radiation, creating what is known as surface plasmon, and this is the basis of the electromagnetic mechanism. The most common metals used in SERS experiments are gold, silver, copper, and aluminum.

The chemical mechanism consists of the enhancement effect due to charge transfer that happens when a molecule is adsorbed on a nanoparticle surface. Often, a redistribution of electronic cloud in the molecule is responsible for the change in the polarizability, and consequently the enhanced Raman dispersion. Generally, molecular adsorption on a silver surface leads to the formation of Ag–N, Ag–S, or Ag–X (X = halogen) bonds, and it can be observed in the 100 to 300 cm^{-1} spectral region.

For SERS measurements, the sample can be set on a nanostructured support and then irradiated by the beam, or the nanoparticles can be located on the sample surface (Figure 2, detail). Several

SERS methods have been developed for heritage applications (Pozzi and Leona 2016).

SERS has been used to analyze samples in the laboratory. However, in-situ SERS measurements were carried out recently by applying a gel with nanoparticles on a painting surface. After the analyses, the gel was removed with minimum damage to the surface. This approach allows noninvasive and in-situ SERS analyses.

Some applications

New applications of Raman spectroscopy are being developed for archaeological science. Most publications related to archaeology are associated to pigments, pottery, stone artifacts, gems, glaze, glass, and other materials. Often microsampling is required, although in-situ analysis for direct measurement on objects and artifacts has become more and more usual.

Raman spectroscopy is particularly useful for the study of pigments in paintings (on canvas and walls) and documents (Edwards and Vandenberghe 2016). The combination of Raman and X-ray spectroscopies (such as X-ray fluorescence, energy dispersive spectrometry, and X-ray diffraction) has proved to be very appropriate for this purpose. In particular, Raman can be used to test for the presence of specific inorganic or organic pigments. Rock painting pigments in prehistoric contexts as well as ancient world and medieval period wall paintings have been examined by this technique. Blue and green colors that are difficult to identify by other methods can be successfully distinguished because of the fingerprint spectra for indigo, lapis lazuli, azurite, Prussian blue, Egyptian blue, malachite, verdigris, and so on. Similarly, yellow pigments may be clearly distinguished (orpiment, lead-tin yellow I and II, Naples yellow, ocher, jarosite, etc.).

Also dyes (organic color extracted from plants) present characteristic spectra. These pigments are sensitive to environmental conditions; and for this reason usually it is necessary to prepare aged reference materials to obtain suitable spectra to carry out their identification. Recent studies have focused on developing new reference spectra for dyestuffs of Mesoamerica.

In particular, the Raman technique can be used to determine the presence of carbon-based paints and pigments in black colors. This method can be appropriated for the characterization of carbonaceous matter: Crystalline carbon materials present well-defined peaks, while amorphous carbon materials show broad bands between 1300 and 1600 cm^{-1} . Some difference in position, width, and relative intensity can be observed for lampblack, ivory black, bistre, bitumen, graphite, and wood charcoal. These differences can be related to natural or artificial origin and structural implications linked to the use of raw materials or to production processes.

In the case of ceramics, it is possible to study the microstructure by applying the Raman technique to the paste and surface of the sherds and to carry out the identification of crystalline phases corresponding to incompletely transformed raw materials or to new phases formed during firing cycles. This approach provides information about the composition and the thermal processes. It is also valid for glass and glaze in the temperature range 700–1450 °C (from pottery luster to high-temperature fired porcelain glaze). The microanalytical features of Raman spectroscopy make it a powerful and unique method for these purposes.

Textile fibers such as linen, cotton, wool, and silk from the ancient world can be studied using the Raman technique if they are in good conservation condition (Edwards and Chalmers 2005). Archaeological fibers present significant fluorescence due to material degradation. SERS on microsamples is a good option for the characterization of these materials. Aged fiber analysis may help to understand the deterioration process under burial conditions (oxidation, hydrolysis, anoxic environment, and thermal degradation). This information can be obtained from Raman spectra signals related to the polymeric chains and chemical bonds.

Mesoamerican and Chinese jades have also been studied by this method. Jadeite and nephrite are clearly identified and differentiated from other green stone minerals. In particular, the principal Raman band of jadeite, the Si-O-Si symmetrical stretching vibration (703 cm^{-1}), may indicate the proportion of jadeite in the artifacts. This technique has contributed to the study of the exploitation of raw material sources

and exchange routes in Asia and Mesoamerica. Complementary methods for this kind of study are Fourier transform infrared spectroscopy (FTIR), X-ray fluorescence (XRF), and particle induced X-ray emission spectroscopy (PIXE).

Precious stones are materials that can be non-destructively studied by Raman spectroscopy, focusing on gem identification and evaluation of the composition, provenance, and genesis of gems (Bersani and Lottici 2016). In particular, the characterization of mineral inclusions by Raman provides a clue to identify the exploitation of beds of raw materials. Rubies, emeralds, garnets, chalcodites, variscites, and other gems have been studied with this approach.

SEE ALSO: Characterization of Pigments; Chemical Mapping; Chemistry in Archaeology; Databases in Archaeology; Dyes; Fibers; Gas Chromatography–Mass Spectrometry (GC-MS); Gemstones; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Instrumental Analysis of Lithics; Nanotechnology and Nanoscience in Conservation; Nondestructive Compositional Analysis of Ceramics; Paper Analysis; Pigment Alteration; Pigments and Binders; PIXE and Material Analysis; Portable X-Ray Fluorescence Spectrometry (pXRF); Raman Spectroscopy in Conservation; Vibrational Spectroscopies; XRD and Materials Analysis

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FURTHER READINGS

Reflectometry

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Reflection and refraction

According to ancient Greek philosophers, human sight was based on a beam of light coming from the eyes, and the picture thus formed of our sensible world was the result of these rays being reflected back by objects and detected by the eyes. In the modern era, this theory has been disproved, because it would require an infinite speed of light to see objects simultaneously at different distances; however, it is a good representation of the way we perceive reality—through reflected signals.

In fact, modern instruments for nondestructive analysis of materials used in a wide array of applications, from the physics of atomic particles to skin cancer detection, work in a similar manner.

From a very generic point of view, reflectometry is concerned with every type of signal coming back from a discontinuity inside a medium (solid, liquid, gas, or mixed) toward which we have sent some kind of energy. In physics, energy is propagated in different ways, such as by energy waves or “kinetic bullets.” Operating in the context of heritage artworks, it is strongly recommended that techniques based on the transfer of kinetic energy, such as a bullet striking a target, should be avoided as far as possible; the bullet’s trajectory could give some information on the structure of the target itself.

In a context where both high penetration of matter and nondestructivity are required, the main choice of researchers will be energy waves. In this domain, two branches can be assumed: The first uses mechanical waves, such as seismic or sound waves; the second uses electromagnetic (EM) waves. EM waves have the incredible property of being able to penetrate and move both

inside matter and in the absolute empty space in the same way, depending only on their frequency and the refractive index of the materials traversed.

The refractive index of a given material (liquid, crystalline, or amorphous) is a measure of how much the speed of light (or other waves such as sound waves) is reduced inside the material. Every time the light (or less specifically an EM wave) encounters a physical interface between two media with different refractive indexes, a reflection occurs. The reflected beam can be detected and measured, giving useful information both on the interface and on the two media.

In reflectance, incident radiation striking a sample can produce two kinds of reflection: diffuse (also called Lambertian) and specular. The radiation that penetrates inside the sample structure interacts with one or more particles and is scattered in all directions (isotropic reflection), and for this reason this component of light is called diffuse reflectance. On a rough or matt surface material, such as textiles (see TEXTILES), pigments, and powders, specular reflected light makes only a very small contribution to the overall signal. In general, every surface has both specular and diffused reflectance (Figure 1).

Diffused reflection contains information on a sample’s compounds and, more specifically, determines its color, whereas in specular reflection each incident ray is symmetrically reflected at the same angle between the incoming beam and the surface normal. It gives information on the source of light and the surface microstructure. In fact, specular reflection is typical of metals, metallic coatings, and glazes (see GLAZES, SLIPS, AND PAINTS). A very useful application of specular reflectance measurements is the study of surface coatings, such as surface-treated metals, paints, and polymers.

Increased path lengths through thin coatings can be achieved using small angles of incidence. Thicker coatings in the micrometer thickness range can be measured using angles of incidence of 30°.

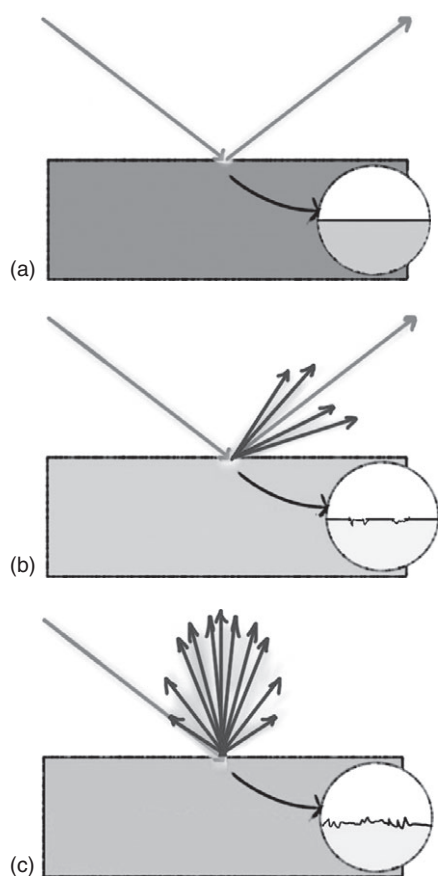


Figure 1 Schema for reflection over a surface. (a) Flat surface (metal), total specular reflection: Ideally the beam is reflected back at the symmetric angle of incident beam. (b) Intermediate case with mixed reflectances. (c) Rough surface (Lambertian reflector): Ideally the whole reflection is diffused isotropically, with no prevalent direction of reflection.

General overview of electromagnetic waves

Different EM radiations interact in different ways with the physical matter of art and archaeological samples.

High-energy rays such as gamma and X-rays penetrate the atom and cause excitation of electrons or nuclear particles, followed by a characteristic reemission (see X-RAY FLUORESCENCE SPECTROMETRY (XRF) and ION BEAM ANALYSIS (PIXE/RBS)). In general, due to the change

of energy of the outward ray, it is unusual to define *reflection* for this kind of high-penetrating radiation.

The same can be said for ultraviolet (UV), which usually causes fluorescence, in which the energy is used to trap electrons in a metastable state and it is then reemitted at lower energy (often in the visible (Vis) range).

On the contrary, in the Vis and near-infrared (NIR) region of the spectrum (380–2500 nm), radiation can interact with structures bigger than a single atom and is reflected back by a multiplicity of different phenomena, such as selective absorption, diffraction (see DIFFRACTION), interference, and scattering.

From a strictly physical point of view, on electromagnetic fields associated with the radiation there is always a process of absorption and reemission, but from a more general point of view, such as in optics, the radiation is reflected, or scattered back, at the same energy level.

Quantitative measurements in the visible part of the EM spectrum (380–780 nm) have great significance for color in the study of heritage objects, through the use of colorimetry. Colorimetry differs from visible spectroscopy (see OPTICAL SPECTROSCOPIES) because it is more connected to the human perception of color.

By taking into consideration the operating conditions of both the observer and the illuminant (i.e., the certified source of light), the values of chromatic coordinates in color spaces can be obtained from the reflectance values of the surface of an object. Different color spaces (RGB, XYZ, Lab, etc.) have been built with the aim of establishing standard color reference naming such that there can be no linguistic misunderstandings. Lab space represents the color space most similar to human perception.

Finally, at higher wavelengths, in mid- and far-infrared (FIR) (see INFRARED REFLECTANCE SPECTROSCOPY) and in the terahertz region, interaction with sample surfaces becomes very complicated in the presence of a large number of absorption energy levels due to the roto-vibrational states of each compound present in the sample and because of black-body radiation. This is the radiation emitted by all objects as a function of their temperature; for room temperature this is centered at 10 microns in the FIR region.

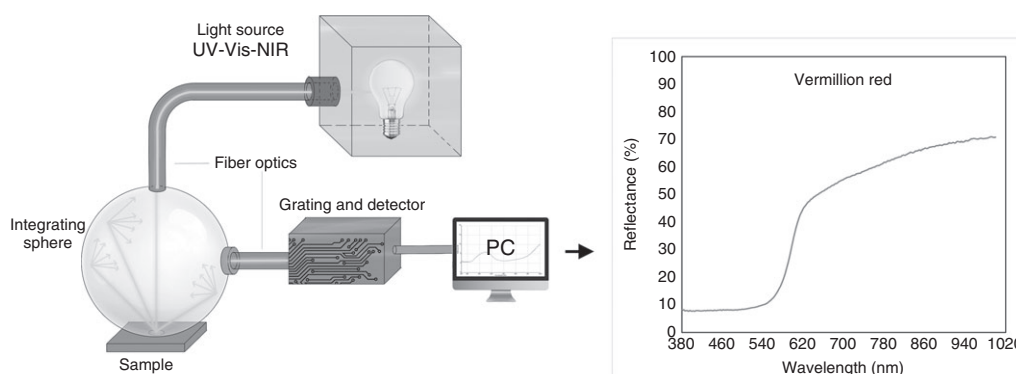


Figure 2 (Left) Schematic representation of a fiber optics reflectance spectrometer (FORS). Light in the long-wave UV, Vis, and NIR is provided by a lamp; through a fiber optic it is focused on a small spot on the sample surface (a few millimeters squared) and then the reflected or backscattered light enters the integrating sphere with almost absolute reflectance whose only exit is the output fiber. This leads the light into a spectrometer where it is dispersed in wavelength with a reflection grating and then projected onto a multiple array detector. (Right) The graph shows a Vis-NIR spectrum of a vermillion sample measured on a fresco in Kobayr church, Republic of Armenia (see Ludwig et al. 2014).

In order to avoid surface reflection, the method of attenuated total reflectance (ATR) (see also INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)) has been developed in mid- and far-IR in order to analyze the compounds of the sample instead of characterizing optically (external reflectance).

Nonionizing radiations (short-penetrating radiation)

Reflectance spectroscopy or spectral reflectometry (SR) is a method of characterizing the optical properties of samples by measuring the reflection of EM radiation coming from an object. In most implementations the wavelength ranges from weak UV to NIR, 200–2500 nm.

With this method, light is shone upon the sample, and this interaction with the sample causes some light to be scattered back—or reflected (hence the name “reflectometry”). The reflected light can be measured by placing detectors along the path of the reflected light. Light is further separated into its wavelength components, and eventually into its various polarization directions (*ellipsometry*).

Figure 2 shows a schematic of a basic system for SR using fiber optics (Bacci 2000). Light, in the

long-wave UV, Vis, and NIR regions, is provided by a multispectral lamp (often halogen plus a deuterium bulb); then through a fiber optic the light is focused on a small area of only a few millimeters squared on the sample surface.

The backscattered (reflected) light enters the integrating sphere with almost absolute reflectance where the only exit point is the output fiber. This fiber leads the light into a spectrometer where diffraction occurs (in general with a reflection grating) and it is then projected onto a multiple array detector.

Both the number of detectors and the width of the light beam determine the spectral resolution of the spectrum. In Figure 2 (right) the actual resolution of the spectrum is only 2.7 nm, whereas the number of detectors is 3,600 over a range of about 900 nm.

In applied spectroscopy, the relationship between the amount of light reflected (diffuse reflectance) and the absorption and scattering properties of a given material was formulated in the 1940s by Kubelka and Munk (Hunt, Gainer, and Pointer 2011):

$$\frac{K}{S} = \frac{(1 - R_{inf})^2}{2R_{inf}}$$

where R_{inf} represents the reflectance of an infinitely thick sample of the material (actually a

few millimeters or less). S and K are scattering and absorption spectral (i.e., wavelength-dependent) coefficients, respectively. They represent the property of the compounds to absorb or reemit the radiation after it has hit the minute particle of pigment or light-diffusing material.

By using a spectra database of similar materials, for example a set of painted pigments (see CHARACTERIZATION OF PIGMENTS) or dye (see DYES), in the same given range of wavelengths, the composition of paint can be deduced, and also what its spectrum looks like in terms of the absolute and relative maxima and minima of the curve.

The reflectance graph displayed in Figure 2 (right) shows the spectra in the Vis-NIR range of a sample of vermillion found in the fourteenth-century fresco in Kobayr church in Armenia (Ludwig et al. 2014). This brilliant red pigment was widely used in the ancient world and it was obtained from cinnabar, a mineral composed of mercuric sulfide (HgS). This kind of spectrum is described as “S-shaped” for its characteristic three-step trend: low value—sharp climb—plateau of high constant reflectance. This reflectance spectrum and therefore its absorbance are characterized by a trend typical of semiconductor materials in which energy is absorbed only from a threshold value.

This behavior is due to the peculiar electronic transition that can be found in pigments such as *minium*, *cadmium yellow*, *cadmium red*, and *orpiment*. The *energy band transition* occurs when all the molecular orbitals of the atoms are close enough to each other that the orbitals become a continuum over all of the crystal, namely energy bands (Bacci 2000). In semiconductors, there are two bands of the named pigments: one filled with electrons and the other empty, separated by an energy gap. When the energy of the incoming radiation is higher than this characteristic gap, the electrons in the full band absorb it in order to empty the band. When the energy of the radiation is lower, it is scattered away. This threshold value determines the typical shape of the spectra of that kind of material, making them easily recognizable.

The absorption spectrum gives the step transition between absorbed and nonabsorbed energies. Spectra with peaks—or more properly bell-shaped sections—are characteristic of the electronic transition between isolated molecular

orbitals. Even more characteristic bands in reflectance spectra can be found, typically in colored glass (see GLASS COLOR), where the color is due to the presence of very low concentrations of the transition metal and the glass itself can be considered as transparent (Fermo et al. 2016).

Other bands of EM radiation, in particular mid- and far-IR (2.5–25 μm), are widely used to identify chemical compounds, thanks to the characteristic, very complex set of absorbance peaks (fingerprint) due to the rotational and vibrational modes (see VIBRATIONAL SPECTROSCOPIES) of both organic and inorganic molecules. This spectroscopy (Fourier transform infrared spectroscopy (FTIR)), however, works in the absorbance spectrum more than in the reflectance spectrum; the signal reflected back is of little interest compared to the signal transmitted through a sample, and therefore FTIR is no longer considered to be a reflectometry technique at all (Khoshhesab 2012). Furthermore, in reflectance mode the sample must be milled and mixed with a nonabsorbing matrix such as KBr to ensure deeper penetration of the incident beam into the sample, in order to increase the contribution of the multi-scattered component. However, the technique cannot be considered as noninvasive and therefore it is not so appropriate for analyzing paintings and delicate works of art.

Recently, devices have been developed for FTIR working over 2.5 μm , which are able to operate in an experimental reflectance set-up with totally contactless measurements and therefore can obtain absorbance peaks as values that are complementary to the reflectance spectra measured.

Finally, it is important to emphasize that in totally contactless applications, such as on frescos or easel paintings, the output spectra can be strongly influenced by gypsum, glue, and the pigments of the painting background (“*preparazione*”) (Bacci 2000). This is due to the higher penetration of IR radiation inside pictorial layers.

Ultra-penetrating radiations (terahertz)

Terahertz reflectometry (see TERAHERTZ IMAGING IN CONSERVATION), using radiation of

some tenths of a millimeter of wavelength, may be used for noninvasive measurement of the thickness of a paint layer (Dandolo, Koch, and Jepsen 2016) as well as for estimation of pigment particle sizes. This aim can be achieved using a scanner over the painted surface. Every discontinuity along the transmission path within the material causes a part of the original signal to be sent back. Monitoring these reflections over time, it is possible to detect structural defects such as delaminations and to distinguish inner structures clearly. However, despite the potentially great penetration of this longer-wave radiation (see GROUND-PENETRATING RADAR and RADAR), terahertz is not yet widely applied in the analysis of art and archaeological objects.

Mechanical reflection (acoustic, ultrasound, and neutrons)

Acoustic waves are another important means of penetrating matter. They do not need an electromagnetic field and are not perturbed by any electromagnetic property of the atoms on their path. In ultrasound, an emitting antenna generates waves that enter the object (usually stone). The wave can be partially reflected every time it reaches an interface inside the propagation medium (for example, a crack or an inclusion of different materials). The waves reflected back to the receiving antenna, the time taken to reach it, and the amplitude of the waves give the impedance of the material and the depth of the crack.

Acoustic waves (20 Hz–200 kHz) have been recently applied in the investigation of heritage materials such as pictorial layers on frescoes, ceramics, or detachments in easel paintings. The acoustic energy absorption diagnostic device (ACEADD) produces diagnostic images using an acoustic source (kHz) with spatial resolution, useful in the restoration and conservation study of artworks (Maev, Green, and Siddiolo 2006). A chirp signal of a combined high-frequency set of acoustic waves can be selected to excite the possible delaminations of painting layers, cutting off the lower frequencies characteristic of the vibration of the massive wood substrate.

Neutron reflectometry (NR) uses neutrons' scattered angles to probe the nuclear composition and magnetic properties of materials characterized by a flat surface (see NEUTRON IMAGING AND TOMOGRAPHY IN CONSERVATION). The detection of the intensity of reflected particles as a function of angle or neutron wavelength gives spectra of reflectivity whose shapes provide information about how the surface is made, including thickness, density, and roughness of any thin films possibly layered on the substrate. The strong interaction of neutrons with hydrogen and deuterons enhances its capability to study mineral compounds characterized by such elements. NR has proved to be useful for studying stone, glass, and ceramic as well as painted surfaces.

SEE ALSO: Flooding

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Scanning Electron Microscopy

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The microscopic and material analysis of heritage materials has a history almost as long as technical microscopy and analytical chemistry themselves. Martin Heinrich Klaproth (1743–1817), who discovered the elements chromium, uranium, zirconium, and titanium and became the first professor of chemistry at the University of Berlin in 1810, had published results about the chemical composition of ancient glass, Greek and Roman bronzes, and coins already around 1800 (Klaproth 1792). Klaproth had to use the chemical techniques of gravimetric analysis and developed new chemical recipes for the separation of copper, lead, and tin for their quantitative determination. Thus large amounts of sample material or even smaller coins had to be dissolved in nitric acid (HNO_3), a procedure that cannot be accepted by archaeologists, curators, or conservators nowadays.

A big change in the material determination and description of archaeological finds, and also artworks, occurred at the beginning of the last century, when physicists and analytical chemists developed the electron microscope (Ruska and Knoll 1931) and microchemical spot tests (Feigl 1954a, 1954b) for which only a few micrograms of material are required. Such investigations were widely accepted and applied in the archaeological sciences, as these tests enable the identification of inorganic as well as organic materials in a first survey. However, for each spot test original sample material had to be taken, which can be a limiting factor in many cases, and only the

presence or absence of a specific element or chemical group is revealed.

After World War II a great number of so-called instrumental techniques for microscopic and material analytical investigations could be developed. Their key benefit, if we compare them to chemical spot tests as well as to optical microscopy, is the simultaneous detection of all or most chemical elements present in or on an object. Furthermore, rapid improvement during the last decades, especially in the area of microelectronics and computer sciences, has led to a great variety of nondestructive or even noninvasive microscopic and analytical techniques.

A word about the terms “nondestructive” and “noninvasive” might be appropriate at this point. For an archaeologist, art historian, or conservator, these terms are identical with “nonsampling.” Furthermore, no changes and alterations must occur or are necessary before, during, or after the analyses. In contrast to that, for the analyst, the terms have the connotation that a specimen of an object, for example, is preserved during the analytical procedure. In that sense the methods of electron microscopy can be seen as nondestructive techniques; and small objects or fragments of archaeological finds that fit into the sample chamber of the instrument can be studied, since, owing to the absorption of electrons in air, the investigations usually have to be carried out under vacuum.

Principles of scanning electron microscopy and electron probe X-ray microanalysis (EPXMA or SEM/EDX, SEM/WDX)

The invention and construction of the electron microscope by Knoll and Ruska (1932) and of the electron microprobe (EMP) by Castaing in the middle of the last century (1951) had an enormous impact on all fields of materials science. Only a decade later, Hornblower (1963) and Ogilvie (1970) suggested the EMP for various applications in archaeometric studies. The EMP combines the possibilities of simultaneous

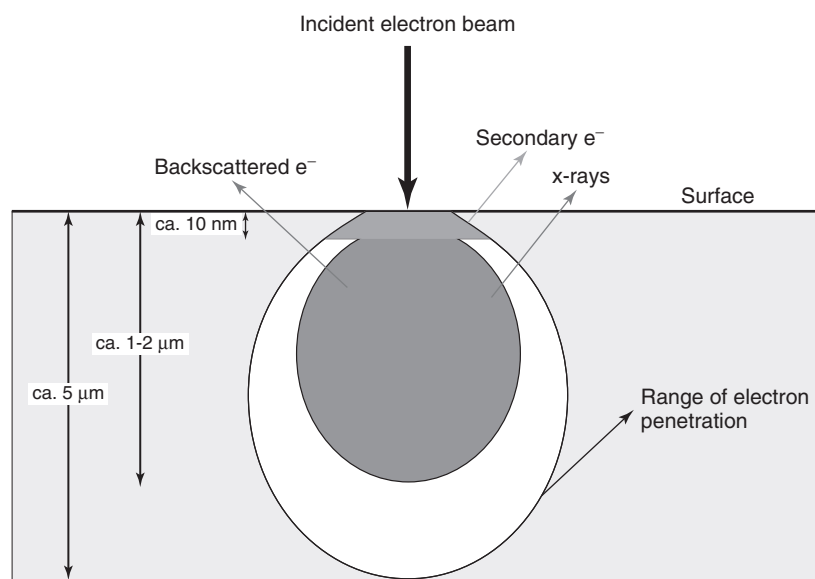


Figure 1 Signals in the scanning electron microscope caused by elastic and inelastic interactions of an incident electron beam with sample matter. On the left-hand side the corresponding information depths of the signals are given with approximation, as these depend on the composition and structure of the material.

Source: Schmidt, Balk, and Blaschke 2004.

imaging and analysis of the microdomains of an archaeological object or sample (Reimer 1985; Reed 1993). Its principle is based on the interaction of a finely focused electron beam emitted by a heated tungsten wire, and the subsequent detection of various emerging signals produced by elastic and inelastic processes in the material (Figure 1).

Measurements of the backscattered electrons (BE) as a function of the position of the electron beam scanning over a predefined area on the sample surface yield an image depicting contrasts between regions dominated by low-Z elements and regions of high-Z elements (so-called “material contrast”; Z refers to the atomic number). Hence the BE image allows for instance the characterization of inhomogeneities (depletions or enrichments of certain elements) at the core or in the surface domains of weathered or corroded materials such as metals (see CHARACTERIZATION OF METALS AND ALLOYS) or glasses (see GLASS AND FAIENCE).

Secondary electrons (SE) are the result of inelastic scattering processes in the sample material that cause for example ionization of electronic

states of the sample atoms. When collected with a secondary electron detector, these secondary electrons originating from the outmost surface layers of the specimen can be used for topographical and morphological imaging of the sample surface—just like a light microscope, but with a much better lateral resolution (approximately 3 nm compared to 1 μm). In the case of (historical) materials, SE images are widely used for characterizing the morphology of their weathered or corroded (and therefore often rough) surfaces.

The interaction of incident primary electrons with sample matter also causes ionization of the inner shells of sample atoms, which results in the emission of characteristic X-rays. As in X-ray fluorescence analysis (XRF; see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), this X-ray radiation can be detected, yielding a characteristic spectrum of the whole sample or enabling rapid qualitative and quantitative analysis of major, minor, and trace components from selected microdomains.

The principle of X-ray microanalysis is based on the photoelectronic absorption process and can best be demonstrated using Bohr’s atomic

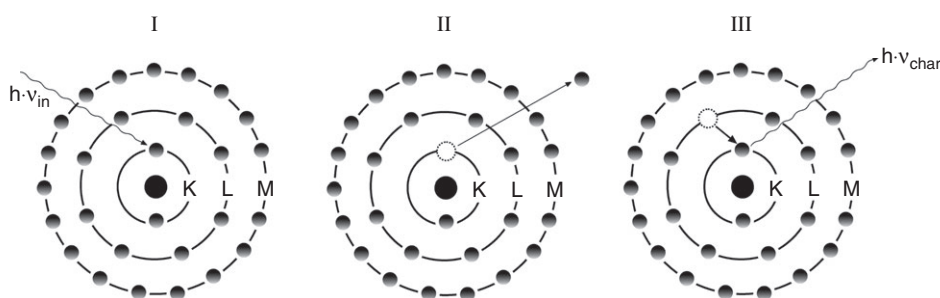


Figure 2 Principle of XRF: The incident X-ray photon (I) causes the ionization of an inner shell (e.g., the K-shell, II). The subsequent relaxation process leads to the emission of X-ray radiation (III) characteristic of the element.

Source: Jenkins 1999.

model (Figure 2): the primary electrons cause the ionization of inner-shell electrons of the material. A vacancy in an inner shell means a highly excited state, and the atoms return to a more stable electronic configuration by emitting X-ray photons ("characteristic" or "element-specific" X-rays) or Auger electrons (not considered here) according to certain quantum-mechanical rules. The specific X-ray photons can be detected in two fundamentally different ways: by a crystal spectrometer, according to their wavelengths ("wavelength-dispersive," WD); or by semiconductor detectors ("energy-dispersive," ED). The major benefit of the latter is the shorter measuring time (typically 50 s), whereas its most significant drawbacks are a lower resolution (typically 130–50 eV) and an inferior detection limit by comparison to the wavelength-dispersive detection mode. As the detected X-rays are characteristic of certain elements, qualitative analysis is straightforward in most cases, while quantitative analysis generally requires either standard materials of known composition and the application of numerical procedures (the so-called "ZAF corrections") or an extensive mathematical treatment of the raw data (the fundamental parameters method).

Measurements in a scanning electron microscope, in combination with either EDX or WDX detection, are in principle nondestructive but, owing to the high absorption of the electrons in air, such instruments have to be operated in vacuum (typically 10^{-5} mbar). As the sample chamber has a limited volume, only small objects like coins or glass fragments can

be analyzed without taking a specimen. In most cases sampling will be required; furthermore, the application of this technique might not be suitable for vacuum-sensitive specimens such as organic or even inorganic materials, for example corroded or weathered glasses, as outgassing of incorporated water may occur. Additionally, thin layers of carbon or gold (typical thickness of 50 nm) have to be sputtered on the sample surface prior to the measurements in order to avoid charging of the specimen when bombarded with electrons. These drawbacks can partly be avoided by using an environmental scanning electron microscope (ESEM) developed in the 1980s, which allows investigations under H_2O vapor atmosphere (pressure approximately 1 Torr) in the sample chamber, while maintaining high vacuum conditions in the microscope column.

The theoretical detection limits of SEM/EDX and SEM/WDX are in the range of 0.1 and 0.01 weight percent (wt.%) respectively, and hence the methods are primarily suited for analyzing major and minor components. In principle, all elements with atomic numbers $Z \geq 3$ (lithium, Li) can be analyzed, but in practice elements with $Z \geq 5$ (boron, B) can be detected depending on the detector technology used. In any case, the electron dose applied onto the specimen should also be kept as low as possible, since numerous recent studies showed more or less severe structural and compositional changes, for example in glass, caused by the incident electron beam.

In summary, SEM/EDX investigations give a clear answer concerning the qualitative and quantitative elemental composition of the bulk

material as well as of the degraded surfaces. Furthermore, the chemical composition and the morphology of corrosion and weathering products yield valuable information on the authenticity of the patina, for instance, and hence on the provenance of a finding. It is therefore not surprising that a close collaboration between archaeological and natural sciences has developed in the last decades. Concerning a series of archaeological findings, the question arises whether these objects exhibit some kind of “characteristic composition,” which can further be used to assign “unknown” objects to a certain place or time of manufacture (in addition to the visual and stylistic analysis), to allocate an object to a particular historical or archaeological context (evidence of trading), to determine the correctness or incorrectness of the claimed provenance, or to explore the technology of manufacturing. The base is therefore to determine when new materials, techniques, or technologies have been introduced or others came out of use. However, the analysis of a great number of dated or precisely datable artifacts is necessary and enables us to set up a *terminus post quem* or a *terminus ante quem* for pigments, metal alloys, or glasses, for example, and also for methods developed or even invented for materials processing or fabrication.

Regardless of the analytical method employed for a given problem, a scientist working in the field of archaeology is often confronted with a huge amount of data, particularly if spectroscopic methods are applied. Therefore the application of suitable multivariate statistical procedures is of particular importance for understanding certain relations in the data. The most frequently applied methods in the field of chemometrics are principal component analysis (PCA), factor analysis (FA), and cluster analysis (CA), which often allow for the identification of (sub)groups of similar objects or outlying observations. These and many more methods are implemented in most commercial or freeware statistical software packages, for example SPSS (SPSS Inc.), SAS (SAS Institute Inc.), or R (Freeware).

Analytical investigations have become an important part in the interdisciplinary cooperation of heritage studies, if the specific technique can be applied to an archaeological object in a nondestructive or even noninvasive way. Among the large variety of modern methods available in

materials science characterization, SEM/EDX has certainly a prevalent place.

SEE ALSO: Electron Microscopy in Conservation; SEM-EDS and Material Analysis; Spectroscopy

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Sequencing DNA

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DNA sequencing is the process by which the order of nucleotides in a DNA molecule is read. Deoxyribonucleic acid (DNA) has a polymeric structure comprising monomers called nucleotides. There are four nucleotides, whose chemical names are abbreviated to A, C, G, and T. These four nucleotides can be linked in any order in linear polymers (“polynucleotides”) millions of nucleotides in length. The order of the nucleotides in a polynucleotide constitutes the DNA sequence. The length of a DNA sequence is measured in base pairs (bp), with 1 bp being a single nucleotide, 1 kilobase pair (kb) being 1,000 bp, and 1 megabase pair (Mb) being 1,000 kb.

A DNA sequence can provide three different types of information relevant to archaeological research. First, a DNA sequence is characteristic of the species of origin and can be used to identify that species. This enables unidentified bone fragments to be characterized, but is more valuable as a means of assessing the disease status of a human skeleton, by identifying the preserved remains of microbial pathogens present in a bone or tooth. Second, those components of the sequence called genes specify the biological characteristics of an individual, which means that DNA sequencing can be used to distinguish males and females, and to provide information on characteristics such as hair color and disease susceptibility. Third, the DNA of an individual, being inherited through generations of parents, grandparents, and so on, provides a record of ancestry. DNA sequencing can therefore reveal the kinship relationships between individuals, and enables individuals to be placed into population groups.

DNA sequencing methodology

The first efficient methods for DNA sequencing were developed in the mid-1970s. One of these, chain-termination sequencing (Sanger, Nicklen, and Coulson 1977), became popular because of its ease of use, reliance on nonhazardous chemicals, and ability to be formatted into automated systems. Virtually all DNA sequencing projects between 1980 and 2005 made use of this method, including the Human Genome Project, which was completed in 2000.

The chain-termination method employs a DNA copying reaction that is carried out in the test tube, driven by a purified DNA polymerase, the type of enzyme that performs DNA synthesis in living cells. A new DNA molecule is synthesized, the sequence of this new “chain” dictated by the sequence of the molecule being copied, the latter referred to as the template. A natural pairing process ensures that an A nucleotide in the template is copied into a T in the DNA that is being made, a C is copied into a G, a G into a C, and a T into an A. The test-tube reaction is performed with a mixture of standard and modified nucleotides, the latter blocking further DNA synthesis and hence causing chain termination. There are four modified nucleotides, called ddA, ddC, ddG, and ddT, each of these labeled with a different fluorescent marker. Each of the new DNA molecules that is synthesized therefore becomes terminated with a modified nucleotide whose identity indicates the identity of the nucleotide in the template at the termination position. The sequencing experiment is designed so that all the DNA molecules that are made begin at the same position on the template DNA. This means that the sequence of the template from that position can be read by placing the chain-terminated molecules in length order, and identifying the terminating nucleotide carried by each one. Separation by length can be achieved by polyacrylamide gel electrophoresis, and the

terminating nucleotide on each molecule can be identified from its fluorescent label. The sequence of the template is therefore read by electrophoresis of the chain-terminated DNA molecules past a fluorescent detector.

The chemical reaction underlying synthesis of a new DNA molecule does not have infinite capacity and the maximum length of sequence that can be read by a single chain-termination experiment is 800 bp. This is not a major problem when ancient DNA (aDNA) from archaeological samples is being studied, because the natural diagenetic processes mean that preserved DNA molecules are highly fragmented derivatives of the original chromosomal molecules, and are rarely longer than 200 bp. The weakness with chain-termination sequencing is the need to purify from the complex mixture of DNA molecules in a sample just those fragments covering the short region of interest, these fragments acting as the templates for the sequencing experiment. With aDNA, this purification step is almost always performed using the polymerase chain reaction (PCR), which results in the repeated copying of a pre-specified DNA segment. The region of interest is therefore amplified from the starting sample by PCR, and the resulting DNA copies used as templates in the DNA sequencing experiment. This approach has two drawbacks. First, a different PCR and chain-termination experiment must be set up for each short (<800 bp) DNA sequence that is sought. The approach is therefore labor-intensive and requires relatively large amounts of starting material in the form of, for example, a bone or tooth extract. Second, copying by PCR is prone to contamination, as minuscule amounts of modern DNA, such as can be deposited on an archaeological sample by handling, will be amplified preferentially compared with the chemically degraded aDNA component of the sample. Despite the use of controls and rigorous technical regimes, the possibility that “aDNA” sequences obtained by PCR and chain-termination sequencing in fact derive from modern contamination can never be entirely excluded.

In genomics research, the desire to obtain complete genome sequences cheaply and rapidly has led to development of new sequencing methods that can provide much greater quantities of data than the chain-termination technique. The first

of these “next generation” methods appeared in the mid-2000s and additional technologies have been introduced regularly since then (Goodwin, McPherson, and McCombie 2016). All of these methods follow the same underlying procedure. The total DNA content of the sample is broken into fragments of approximately 200 bp and the fragments immobilized as individual units on a solid support in an array format. All of the fragments are then sequenced in parallel. The various technologies that are available employ different techniques for the sequencing step, but most are based on synthesis of a copy of each immobilized fragment, the order of nucleotides incorporated into this copy being read as the reaction progresses. For example, the procedure referred to as Illumina sequencing makes use of fluorescently labeled nucleotides, with each addition to the DNA molecule that is being synthesized identified by detection of the label carried by that nucleotide. Other approaches, such as the ion torrent and pyrosequencing methods, do not directly detect the nucleotide addition but instead detect the release of hydrogen atoms and phosphate molecule, respectively, that accompanies each nucleotide addition. Nucleotides are therefore applied one after the other in a repetitive series (e.g., A, followed by C, followed by G, followed by T, followed by A, etc.). If a nucleotide is unincorporated, then it is washed away and replaced with the next in the series. When the correct nucleotide is applied, and added to the end of the molecule being synthesized, the hydrogen or phosphate release is detected. The step-by-step addition of nucleotides to the growing DNA chain can therefore be followed, enabling the sequence of the template molecule to be read.

Regardless of the detailed methodology, the outcome of a next generation experiment is a dataset of millions of short sequence reads, representing all of the DNA fragments in the original sample. Analyzing such vast amounts of data presents a computational challenge, but the importance of sequencing in genomics research means that considerable effort has been put into development of bioinformatics pipelines for the reconstruction of complete genome sequences from next generation reads, or alternatively for identification of reads representing genes or other DNA regions of interest. These pipelines

are readily transferable to aDNA projects. The use of a next generation method does not entirely solve the problems that arise if an archaeological sample is contaminated with modern DNA, and a rigorous technical regime must still be followed to prevent contamination. The advantage of next generation sequencing in this regard is that the vast amount of sequence data makes possible a statistical approach, based on analysis of individual reads for sequencing errors that signal the presence of nucleotide breakdown products resulting from diagenesis, enabling a post-hoc assessment of the likelihood that the reads are authentic aDNA.

DNA sequencing applications in archaeological science

Whether using the chain-termination method or a next generation approach, the applications of DNA sequencing in archaeology are dependent on aDNA actually being preserved in the samples under study. Surprisingly few attempts have been made to understand the diagenetic processes responsible for DNA breakdown in any type of biological material, most of the information coming from observation of DNA presence or absence in materials of different types and ages, rather than from a predictive approach based on measured rates of DNA decay. These observations suggest that aDNA can be sequenced from bones and teeth up to one million years in age, but for this age to be reached the samples must be preserved under relatively cold and/or dry conditions. Under temperate and moist conditions, the DNA content of a bone can decline rapidly over a period of a few centuries or even decades. It is also clear that DNA decay in bones accelerates after excavation, possibly because removal from the burial environment and re-exposure to air leads to a resurgence of microbial activity within the bone. Natural and artificial mummies, as well as explants such as hair, have also yielded DNA sequences, but these types of material have been less extensively studied and the time limits for DNA preservation are unknown. Desiccated plant remains up to several thousand years in age can contain relatively well-preserved aDNA, but charred remains are poor sources, because of the

rapid DNA breakdown that occurs at the temperatures associated with the charring process.

Despite the challenges resulting from the unpredictable preservation of aDNA and the possibility of contamination, DNA sequencing has had a remarkable impact on archaeological research since the late 1980s when the survival of DNA in bone was first demonstrated. This impact has encompassed areas of archaeological endeavor from interpretation of individual sites to broad hypotheses regarding biological and cultural evolution. At the level of individual site interpretation, DNA sequencing has been used extensively in sex identification of skeletons for which conventional typing by osteological methods is not possible. This approach has been particularly informative with infant and neonate skeletons, which have no sex-specific osteological distinctions, and has enabled hypotheses regarding infanticide to be tested. For example, 12 of 35 infant burials from a Roman-British villa at Hambledon, UK, were typed in this way, seven of the infants being shown to be female and five male (Abu-Mandil Hassan et al. 2014). This unskewed ratio suggested that, contrary to previous reports, sex-specific infanticide was not being practiced at this site. With these samples, DNA sequencing was also carried out with segments of the mitochondrial DNA of the infants, enabling maternal relationships to be assessed. No two infants had the same mitochondrial sequence, indicating that each was the child of a different mother. Again, this information helped to dispel previous interpretations of the site as a Roman brothel.

DNA sequencing has also been used to confirm and extend the paleopathological examination of human remains. This approach has been most successful with tuberculosis (TB). Although mainly a disease of the pulmonary system, 3–5 percent of those individuals who become infected with TB progress to an osteological stage, during which *Mycobacterium tuberculosis* bacteria spread via the blood and lymphatic systems to the bones, sometimes resulting in lesions to the thoracic and/or lumbar vertebrae and possibly destruction of the joint surfaces of the knees and hips. None of these changes is diagnostic of TB and, though indicative, they do not constitute proof of infection. The vast majority of cases that display only the pulmonary form of the disease present no osteological indicators, other than

occasional new bone formation on the visceral surfaces of ribs, which is associated with various types of pulmonary infection and again is not diagnostic for TB. Greater precision in the diagnosis of TB has been achieved by sequencing, which has identified *M. tuberculosis* DNA in extracts from skeletons displaying TB lesions and also from skeletons with no indicators of the disease (Donoghue et al. 2015). This work has progressed to the stage where it is possible to use DNA sequencing to distinguish between different subtypes of the bacterium, enabling direct examination of the evolution of the disease over the last 2,000 years (Müller, Roberts, and Brown 2015). There have been similar successes in sequencing plague bacilli from human remains and in confirming osteological detections of leprosy, but the DNA sequencing approach to paleopathology is not unlimited in scope. To use sequencing to detect a pathogen, the DNA of that pathogen must be present in the bones or teeth at the time of death, or must find its way into the skeleton by absorption from, for example, the bone marrow. This is not the case with all diseases, as with many infections the pathogen load can be quite small at the time of death, or might be restricted to the stomach or intestines, resulting in very little pathogen DNA being preserved in the skeleton.

Sequencing of DNA from plant remains has revealed aspects of the evolution of domesticated crops, especially with maize, which is amenable in this regard because of the availability of desiccated remains from various sites in the Americas (Jaenicke-Després et al. 2003). However, the most interesting discoveries have come from analysis of barley and other Old World crops preserved at Qasr Ibrim on the upper Nile. This site was occupied for 3,000 years until a few hundred years ago, and remains of crops grown at the site have been recovered from several excavation levels. DNA sequencing of these remains has revealed genetic adaptations that enabled these plants to be cultivated in the hot and arid conditions present at the site (Smith et al. 2017). The information obtained by these studies is interesting with regards to the development and maintenance of sustainable agriculture at Qasr Ibrim, and is also relevant to the efforts of plant biologists to breed new varieties of crops better able to resist modern climate change.

Returning to the sequencing of human DNA, the area of research that has had the most broad-ranging impact on both archaeological and human evolutionary studies has been the assembly of complete genome sequences for extinct hominins and prehistoric examples of *H. sapiens* (Llamas, Willerslev, and Orlando 2017). The first Neanderthal genome sequence, published in 2010, was a composite of three 38,000-year-old samples from a cave in Vindija, Croatia. This was followed by a more accurate sequence from a single individual of approximately 50,000 years from Denisova Cave in the Altai Mountains, Siberia. This cave also contained other bone fragments and teeth that initially yielded a mitochondrial DNA sequence that was so different from those of Neanderthals and modern humans as to suggest a new species, although subsequent sequencing of the nuclear genome identified these “Denisovans” as a sister group of Neanderthals. Comparisons between the Neanderthal, Denisovan, and *H. sapiens* genomes have revealed that these three types of hominin interbred, with some 2.0 percent of the modern European genome obtained from Neanderthals, and the modern Asian and Oceania human genomes similarly influenced by introgression of DNA from Denisovans. One of the more intriguing discoveries of recent years has been the presence in Tibetans and some other Asians of a variant of the EPAS1 gene, which is absent in other modern human populations but was present in Denisovans, and which is thought to have been obtained by the Asian groups from that source. The specific role of the EPAS1 gene is in the response of humans to low oxygen environments, the variant present in Tibetans providing enhanced tolerance to the reduced oxygen levels at high altitudes. The ability of humans to colonize the high mountainous regions of the Himalayas may therefore be due to past interbreeding with Denisovans.

SEE ALSO: DNA: Mitochondrial; DNA: Next Generation Sequencing; Genetics: Ancient; Genomics: Ancient

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Spectroscopy

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We generally define spectroscopic processes as all interactions of radiation with matter involving a quantized exchange in energy. In more general terms, because of the De Broglie concept of wave-particle duality, the incident probe on the analyzed material may be electromagnetic radiation (described as waves or photons) or particles (electrons, neutrons, protons). In all instances, we consider the transfer of energy quanta from the probing beam to the electrons or the nuclei of the investigated atoms (Calas and Hawthorne, in Hawthorne 1988). The photon energy due to an electron transition between an upper atomic level k (of energy E_k) and a lower level of energy E_i is:

$$\Delta E = E_k - E_i = h\nu = hc\sigma = hc/\lambda_{\text{vac}}$$

where ν is the frequency, σ the wavenumber in vacuum, and λ_{vac} the wavelength in vacuum (Atkins, de Paula, and Keeler 2017). The energy exchange is commonly treated in terms of *absorption* or *emission*. Rigorously, spectroscopy deals with the description and quantification of the excitation processes, whereas spectrometry is involved with the instrumental measurement of the absorbed or emitted signals. The two terms, however, are often used interchangeably.

During the absorption process there is a transfer of energy from the incident beam to the atoms in the material, and consequently the excitation of the electrons or the nuclei particles from the ground state to an excited state. The change in energy level is defined as a transition between states. We measure the frequency and the magnitude of the absorbed radiation in order to obtain specific information on the energy levels of the atoms to be investigated. The energy of the probe determines which energy levels are excited: As a first approximation, γ -rays excite nuclear levels, high-energy X-rays excite core

electrons, soft X-rays excite outer electrons, ultraviolet (UV) and visible radiations excite valence electrons, and infrared (IR) radiation excites molecular vibrations and phonon waves. The experimental techniques measuring the energy dependence of the absorption of radiation from matter are called *absorption spectroscopies*. Experimental techniques of this kind are, for example, atomic absorption spectroscopy, IR absorption spectroscopy (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)), and X-ray absorption spectroscopy (see X-RAY ABSORPTION SPECTROSCOPY (XAS, EXAFS, XANES)).

The emission of radiation from the atoms upon decay from the excited state to the ground state (often involving transitions to intermediate energy levels) is also a powerful source of information on the intrinsic energy states of the atoms in the material. This is due to the coupling of the absorbed radiation to internal atomic processes, which causes reemission of radiation having different frequency. The frequency shift and the intensity of the emitted radiation are related to the chemical nature and environment of the atoms and are measured by a number of *emission spectroscopies*. Experimental techniques based on the measurement of emitted radiation are, for example, Raman spectroscopy (see RAMAN SPECTROSCOPY), X-ray fluorescence (XRF) spectroscopy (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), laser-induced breakdown spectroscopy (LIBS) (see LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS)), and optical emission spectroscopy (OMS). Much like in absorption spectroscopies, different information concerning the atoms is obtained depending on the energy of the emitted radiation: γ -rays yield information on the nature and state of the nuclei (such as in Mössbauer spectroscopy (see MÖSSBAUER SPECTROSCOPY)); hard X-rays emitted from the ionization of core electrons yield information on the electronic structure, and thus on the chemical composition (such as in XRF and portable XRF (pXRF); see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)); and soft X-rays yield information on the valence of

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atomic species (such as in X-ray photon electron spectroscopy (XPS)). The emission of characteristic visible radiation from outer electronic levels may yield chemical information by OES or LIBS, whereas Raman scattering (see RAMAN SPECTROSCOPY) probes molecular vibrations and phonon waves in solids and may usefully be employed to identify molecules and inorganic compounds.

Only the most diffused spectroscopic techniques are treated in the *Encyclopedia*; nonetheless, it should be appreciated that spectroscopic concepts and experiments are fundamental to any analytical approach to archaeological materials.

SEE ALSO: Infrared Reflectance Spectroscopy

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Thermoluminescence

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Thermally stimulated luminescence, or thermoluminescence (TL), is a property of many insulating materials, mainly in their crystalline form. It is a weak emission of light when they are heated, provided that they have been previously irradiated by ionizing radiation. Because the intensity of the emitted light is proportional to the amount of absorbed radiation (the “dose”), TL is mainly exploited as a dosimetric technique, that is, for measuring the absorbed dose.

In archaeology, TL is a means of dating ancient ceramic artifacts. In fact, crystalline inclusions are contained in the clay which originates from the ceramic material. These inclusions act as dosimeters for the natural radiation always present in any environment.

In extreme synthesis, the more intense the TL emitted by a ceramic, the higher its absorbed dose, and hence the longer is the time passed since the zeroing of the TL signal, when clay gave origin to the ceramic in the kiln. Practically, the more intense the TL, the older the ceramic.

The main dosimetric materials contained in ceramics are quartz (Martini 2014) and feldspars, but many other crystals may be present. TL is produced due to the presence of defects in the crystalline lattice. These defects can act as “traps” for the electrons released by the ionizing radiation. The following heating can “detrap” the electrons, which recombine in other defects, known as “luminescence centers,” which emit TL.

The possibility of dating pottery by TL was first proposed in 1960 at the Universities of Berne and California. Later, it was diffused as a dating technique in many countries and TL dating laboratories soon opened all over the world. Since 1978, the researchers involved have regularly gathered at the International Conference on Luminescence and electron spin resonance dating (LED), nowadays held every third year. TL soon had a dating

ally in optically stimulated luminescence (OSL), a related phenomenon exploiting light instead of heat to detrap the electrons. Because the zeroing event of OSL is the exposure to light, this technique is mainly exploited for dating the deposition of geologic sediments.

Both TL and OSL are absolute dating techniques, giving calendar results that do not need any external calibration. The ages obtained by TL range from a few tens to a few thousands of years, covering the whole period of the diffusion of ceramics.

The accuracy of a single TL date is typically around 10 percent of the age. When dating a number of coeval samples, the error associated with the average age can reduce to 4–6 percent. The basic equation for TL dating (and for every luminescence dating technique) is:

$$\text{Age (years)} = \frac{\text{Total absorbed dose}}{\text{Dose rate (Dose absorbed per year)}} \quad (1)$$

This formula gives the years since the last zeroing event (for TL, a heating to some hundred degrees Centigrade; Wagner 2004) experienced by the sample. For ceramics, this event generally corresponds to the firing in the kiln, which causes the release of any previously trapped electron.

Figure 1 shows a few TL curves (called “glow curves”) from ceramics of different age and origin. The glow curve represents the light emitted by a small aliquot of ceramic while heated from room temperature to about 500 °C. Such light is invisible to the naked eye and has to be detected by sensitive electronic devices like photomultipliers.

Looking at the scale of TL intensity (y-axes in Figure 1) it can be noted how different they are: The maximum intensity of the Etruscan bucchero is more than 40 times the intensity of the Renaissance bas-relief. This is only partly due to their different ages, and mainly due to the amount of crystalline inclusions: Evidently, they are much more present in the Etruscan object than the Renaissance one. To take these differences into account, artificial irradiation in a laboratory is necessary in order to assess the sensitivity to irradiation, as described in the following text.

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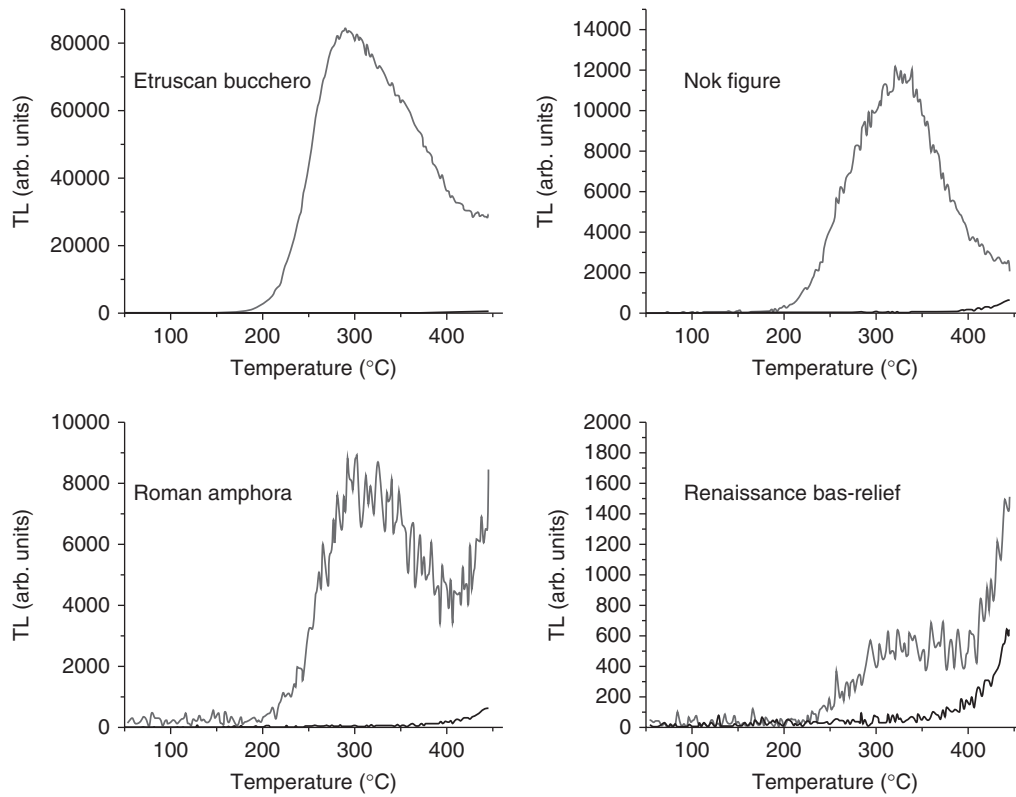


Figure 1 Top curves: typical TL emission of different potteries. Clockwise from top left: Etruscan bucchero vase, sixth century BCE; Nok figurine, second century CE; Roman amphora, first century CE; Renaissance Florentine bas-relief, fifteenth century CE. Bottom curves indicate signal background.

The total absorbed dose (equation 1) is evaluated through TL measurements, after irradiation by calibrated radioactive sources on small samples already irradiated by the natural radioactivity. This is called the “additive dose” technique. The typical linear TL growth versus irradiation dose is shown in Figure 2 for a Roman amphora. The SI unit for the energy absorbed as a consequence of the interaction of ionizing radiation with matter, the absorbed dose, is the Gray, 1 Gy corresponding to 1 Joule/kg.

Responsible for the absorption of this energy, and consequently to produce TL, are the naturally occurring radioisotopes present in ceramic materials and in surrounding soils, mainly uranium and thorium radioactive families and ^{40}K (a smaller contribution is given by ^{87}Rb and cosmic rays). They emit α , β , and γ radiation which interact with matter and lose their energy, part of it being converted into trapped electrons. Typical

values of absorbed dose range from fractions of Gray to a few tens of Gray. The annual dose rate usually ranges from 1 to 10 mGy/year, because the radioactivity concentrations vary from one ceramic to another and from one soil to the next. α and β radiations, characterized by very short ranges, come from the internal radioactivity of the ceramic itself, while the environment contributes cosmic rays plus γ radiation which comes from a range of about 0.3 m around the sample.

TL dating requires small samples to be taken from the analyzed object. The necessary sample can be as small as a few tens of milligrams, when just a qualitative response is required as in an authenticity test. On the contrary, some grams of material are necessary to reach a higher dating precision.

Two main TL dating techniques have been developed: the fine-grain technique (Zimmermann 1971) and the inclusion technique (Fleming

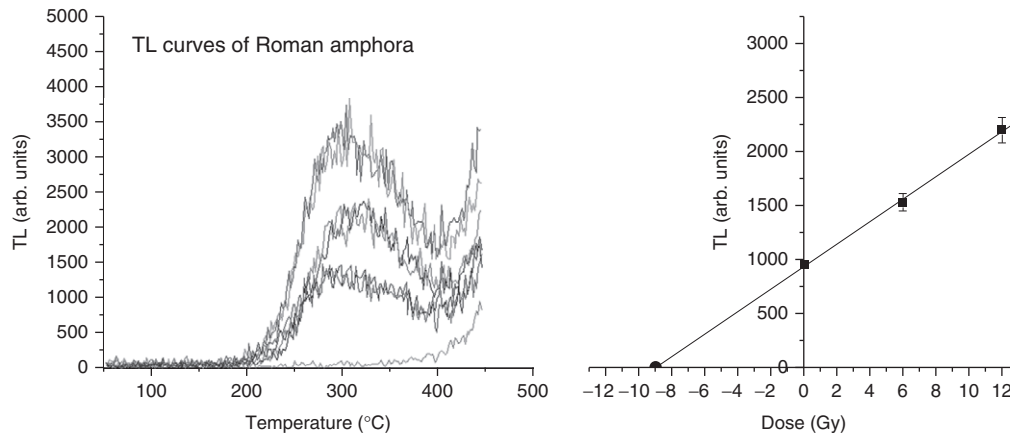


Figure 2 Roman amphora (first century CE). (Left) TL curves induced by different irradiation doses (0–12 Gy) added to the natural dose. (Right) Corresponding linear TL growth.

1970). They prescribe two different recipes for preparing the ceramic samples in order to measure the TL signal and hence the total absorbed dose (equation 1).

In the first case, all the mineral grains originally present in the ceramic paste are taken, only selecting those grains that are small enough to allow full penetration by the short-range α particles (about 20–30 μm). The suitable grain size is 1–8 μm and for TL measurement it must be obtained in the form of a thin layer of a few microns thickness. This technique has the advantage of avoiding mineral selection, but the TL response to α irradiation, which is not the same as β and γ , has to be measured. Furthermore, possible adverse TL characteristics can occur, such as the anomalous fading of feldspars, an unpredictable escaping of electrons from deep traps at ambient temperature, and spurious TL.

The inclusion technique prescribes both granulometric and mineralogical separation. It uses only quartz grains of 80–120 μm dimension, that is, those that have experienced almost only β and γ irradiation. TL measurements are made on such quartz grains once their outer layer is etched away, so that the inner core are unaffected by the superficial interaction with α particles. TL is then only due to β , γ , and cosmic rays. The inclusion technique is based on quartz whose TL characteristics are well known and free from anomalous fading. The amount of material needed, often in the order of grams, depends on the concentration of quartz in the ceramics.

The dose rate (equation 1) assessment requires taking into account how the different components of radioactive decay interact with matter and transfer their energy to the ceramic (Aitken 1985). The adopted approach is the *infinite matrix assumption*: Within a volume greater than the penetration depth of the radiation, the rate of absorbed energy is equal to the rate of emitted energy. In other words, if the matrix is uniform (both in radioactivity and absorption coefficient), the dose—that is, the energy absorbed per unit mass—is equal to the energy emitted per unit mass, which can be calculated from the radioactivity concentration.

However, it must be noted that in almost every ceramic, some water is contained, or it has been contained over the centuries, which means that part of the emitted energy has been absorbed by water and not by the ceramic itself. In these cases, the effective annual dose is lower than the calculated one on the basis of the radioactive content of the ceramic and soil.

To practically evaluate the annual dose rate for equation (1), several techniques and methods have been developed. One possibility is to measure, with radiometric techniques, the radioactivity concentrations of the ceramic and soil, and then derive the corresponding contributions by means of purposely evaluated conversion factors, specific for the adopted dating method (Guérin, Mercier, and Adamiec 2011). Other calculations for additional experimental evaluations

like radon escape, disequilibrium, and leaching are also required.

Alternatively, dosimetric techniques allow us to directly obtain the various components of the dose rate with high precision and accuracy. Specifically, for gamma dosimetry, a capsule containing a few TL dosimeters is buried for a few months in place of the sherd to be dated to record the exact dose rate it experienced from outside.

Finally, the cosmic rays: In most cases their contribution is sufficiently small that a standard value of 0.15 mGy/year can be assumed for buried samples. Only in special cases (low sample radioactivity, high altitude) should adjustment of the standard value be considered.

The procedure for error-limit assessment is to calculate the percentage error in the date corresponding to a given error in each of the quantities or parameters on which the date is based. The random errors are due to luminescence measurements and to annual dose evaluations, while the systematic errors are mainly due to the calibration of laboratory radioactive sources. If TL age derives, as recommended, from the measurement of at least three coeval samples, the best value for the age of the context is the weighted mean of the individual ages. The overall error is the square root of the sum of the squares of the individual errors, and a standard error on the average age is also quoted.

As already mentioned, TL is typically applied to ceramic material, which means not only pottery but also bricks; therefore, the dating of buildings can be afforded. TL can also be used to date the clay core of bronze statues, as mentioned in the following case study.

Like any other dating technique, TL can be used if the conditions of its applicability are satisfied, keeping in mind its intrinsic characteristics. TL dates the last heating of the material, which means that in some cases the calculated age might not be related to the archaeological event under study, owing to the possibility of reuse (TL age older than expected), or restoration or fire (TL age younger than expected). When applied to archaeology, a detailed stratigraphic analysis is very useful before sampling, in order to identify samples whose age can be correlated to that of the archaeological layer.

To be successful, a dating campaign must be carefully set up (stratigraphic analysis, selection of the key sampling points, availability of materials and soils). No precise dating can be performed on samples whose archaeological context was lost or questionable, nor should analyses be done on a single sample, but at least on three coeval samples. The contemporary use of other techniques like radiocarbon, OSL, or dendrochronology is recommended, if affordable. The precision of the results can be further enhanced by an appropriate use of the Bayesian statistic (see BAYESIAN STATISTICS) that combines in a single formal analysis the experimental results with historic information about samples and provenance sites.

Case studies

In many cases, TL dating allows establishing, deepening, or refining the chronology of an excavation site and, through it, of a past society. The time span of the rise and fall of the Peruvian Moche culture at the Sipán site and assessment of the continuity of the Mỹ Sơn Hindu religious settlement from the fourth century to a couple of centuries beyond the Vietnamese military conquest in the fifteenth century are just two examples of the integrated approach mentioned above (Maspero, Sibilia, and Martini 2016).

Sipán is a Moche site located in the desert coastal zone of northern Peru, consisting of two mud-brick pyramids higher than 35 m, and a smaller connecting platform. Since its fortuitous discovery in 1987, it has soon appeared as one of the richest and most extraordinary funeral complexes of the region: Sixteen tombs have been excavated, revealing precious and enormous information regarding the Moche culture, which developed in that region from 100 to 700 CE. TL dating was performed, together with radiocarbon accelerator mass spectrometry (AMS) dating, on a number of samples from the key structures of the settlement, to establish a reliable, scientific-based chronology, particularly controversial for the final phase. Our dating results documented the occupation of the site since the beginning of the third century until its abandonment during the sixth century period. Moreover, the production and use of ceramics stylistically

referred to the more ancient phases (Moche II and III) continued without interruption until the abandonment of the site (Aimi et al. 2016; Maspero et al. 2016).

Although TL has become well established in the field of archaeology, it has very good potential also in the history of buildings with the possibility of identifying alterations, repairs, and restoration phases that may have occurred since the original construction (Guibert et al. 2009).

Mỹ So'n, the Vietnamese sacred site of the kingdom of Champa (fourth–fifteenth century CE), inscribed since 1999 in the UNESCO World Heritage List, consists of the remains of a series of impressive Hindu tower temples, which have survived centuries of abandonment, severe war damages, and controversial restorations. Mỹ So'n is an archaeological site of primary importance for the knowledge of Vietnamese history and culture. A Vietnamese–Italian joint research project allowed archaeological excavation on site, focusing on the G temple group. Prior to the consolidation and restoration works, more than 50 samples were taken from almost all the structures of one of the temples and dated by TL. The results allowed archaeologists to identify and place in chronological sequence the edification of the different buildings, which occurred at various times during the twelfth century. Moreover, older potteries were found, reused from other abandoned buildings in the same area (Martini et al. 2008; Maspero et al. 2016).

A further dating application is to clay cores, the ceramics-like residual of the fusion activity of bronzes, fired during the fusion itself. In many cases, their analysis can be crucial to determine the age of renowned masterpieces, whose chronological assignment is sometimes controversial. This is the case with the Lupa Capitolina, a symbol of Rome, traditionally considered to be of Etruscan age. TL dating, together with results of the analysis of alloys and production techniques, definitely excluded Etruscan production, confirming its fusion in the medieval age (Martini and Sibilia 2009).

When TL dating cannot be performed properly—for instance, in the case of single samples out of context—a simplified TL test to check their authenticity can be done. A very small amount of ceramic is needed, some tens of milligrams, to measure the total amount of TL of

the sample in order to verify its compatibility with the expected value, inferred from the presumed age, without measuring its radioactive content, which needs much more sample. In other words, the TL test only tells us if a vase is *antique* or *young*, allowing us to distinguish between an original piece and a modern copy.

SEE ALSO: Dating and Electron Spin Resonance (ESR); Dating and Infrared Stimulated Luminescence; Dating and Optically Stimulated Luminescence; Dating Ceramics and Luminescence; Dating in Archaeology; Geoarchaeology; Optically Stimulated Luminescence

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Transmission Electron Microscopy

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Transmission electron microscopy (TEM), together with the companion technique, scanning electron microscopy (SEM), is regarded as one of the most powerful characterization tools for materials (Newbury and Williams 2000). This is also reflected in the abundant literature, textbooks, and specialized journals concerning these two microscopy techniques. A variety of specific instrumentation has been developed over the years to comply with the requirements of different classes of materials (see SCANNING ELECTRON MICROSCOPY). TEM and SEM, in association with relevant spectroscopy tools, such as energy dispersive X-ray spectroscopy, are gaining increasing importance in the study of materials for conservation (see ELECTRON MICROSCOPY IN CONSERVATION) and archaeology (see TEM AND ARCHAEOLOGICAL MATERIALS).

The development of the instrumentation for modern TEM began in the 1930s with the pioneering experiments by M. Knoll and E. Ruska. Ruska was awarded the Nobel Prize in Physics (in 1986) for his major contributions to the fundamental principles of electron microscopy (Ruska 1987). The initial idea for the development of electron microscopy was to overcome the submicrometric resolution limits of optical microscopy (see OPTICAL MICROSCOPY), essentially determined by the wavelength of visible light (200–700 nm), by using high-energy electrons. The De Broglie wavelength of electrons accelerated by voltages of 100–400 kV lies in the range of 0.00370–0.00164 nm. The ultimate resolution in state-of-the-art electron microscopes is limited by the aberrations affecting the magnetic lenses, particularly the objective lens, present in the optoelectronic column of the microscope. Sub-angstrom resolution has been achieved by compensating for these aberrations, particularly

the spherical and chromatic aberrations, using suitable correction systems and energy filters, with the possibility of imaging atomic arrangements and relevant defects with high-resolution TEM (HRTEM) images (Haider et al. 2009). HRTEM requires significant software support for modeling images obtained using *phase contrast* principles, based on the interference among the many beams crossing the observed sample region. The specific requirements for an observable HRTEM specimen are definitely more restrictive, particularly with regard to its limiting thickness and homogeneity, as compared with conventional TEM specimens. However, atomic resolution images are not usually required in archaeological science, and in this field, conventional TEM is a more important experimental tool for achieving a complete microstructural, crystallographic, and chemical characterization of the analyzed materials. This can be achieved thanks to the flexible imaging modes, electron diffraction methodologies and high spatial resolution spectroscopies.

Contrast in TEM images is determined by *mass thickness*, *diffraction* or, indeed quite commonly, a combination of the two. Mass thickness contrast is determined by the differential absorption of electrons by regions of the specimen having different average atomic number and therefore electron absorption coefficients.

Diffraction (see DIFFRACTION) *contrast* is determined by the scattering phenomena of the electrons by the crystalline lattice and structural defects present in the sample. Bright field (BF) and dark field (DF) images are obtained using the transmitted and diffracted beams respectively. These images convey information on the structural features of the investigated specimen, as shown by the images in Figure 1. The BF (Figure 1a) and DF (Figure 1b) images from the same field of view of a synthetic fluorite (Ca₂F) specimen are shown, demonstrating the reason for the two complementary imaging modes. BF images are produced by the transmitted (not deflected) beam. The transmitted beam is the brightest spot at the center of the selected area electron diffraction (SAED) pattern (Figure 1c),

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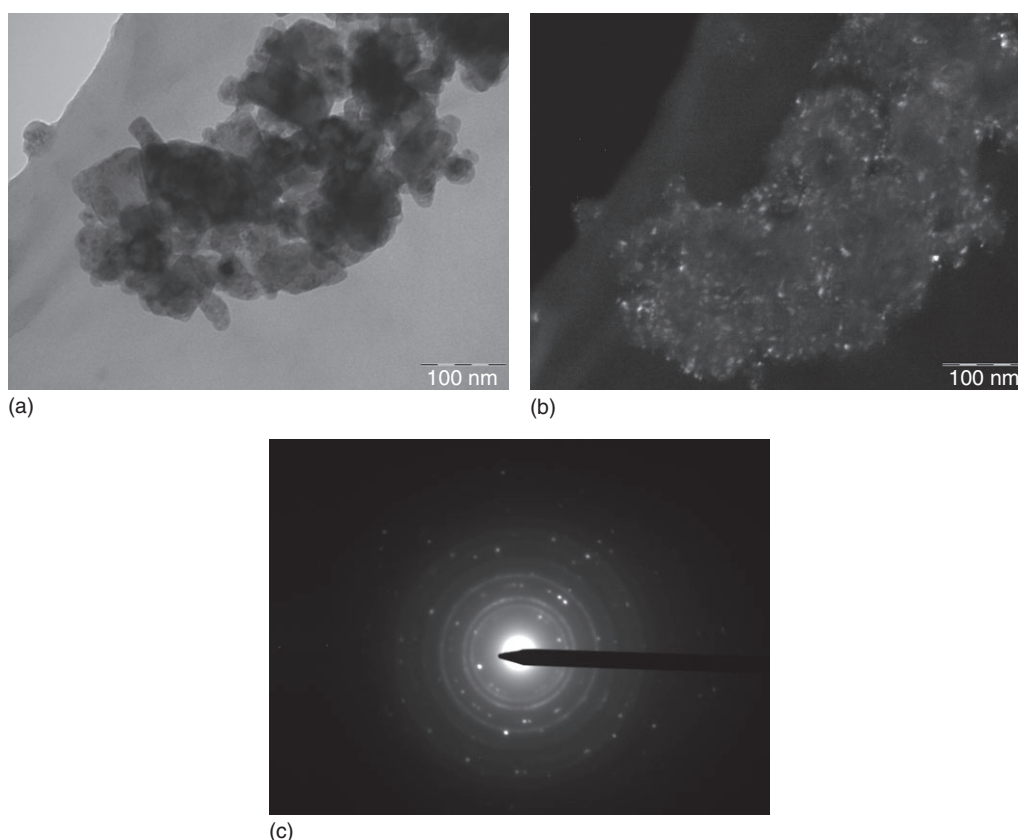


Figure 1 TEM micrographs of a synthetic fluorite (CaF_2) powder sample. Diffraction contrast: (a) BF image; (b) DF image. (c) The related SAED pattern. (Courtesy of Dr Gloria Ischia, University of Trento, unpublished data).

surrounded by the diffracted beams. From the DF image, the average crystallite size can be better appreciated, looking at the brighter speckles originating from individual scattering domains.

Other important imaging modes can be implemented in a TEM through the scanning transmission electron microscopy (STEM) mode, in which, like in conventional scanning electron microscopes, a focused beam is scanned point-by-point across the sample surface. The transmitted signals are collected by specific detectors and form BF and DF images accordingly. An additional imaging option is available for DF images, associated with high-angle scattered electrons, forming the so-called high-angle annular (detector) dark field (HAADF) images. Since electron elastic scattering depends on the atomic number, these images are usually referred to as

Z-contrast images. It is worth saying that the highly coherent electron beam used in STEM mode, and the incoherence introduced in the transmitted beam by the high-angle scattering, is somewhat analogous to the *phase contrast* used in HRTEM. In fact, in STEM subnanometric resolutions can also be achieved, and for this reason this technique should also be regarded as a high-resolution imaging tool (Erni et al. 2009).

Electron diffraction, already mentioned with reference to *diffraction contrast*, also provides essential data for crystallographic investigations, for which SAED is probably the most commonly used methodology. A physical aperture is inserted in the first image plane of the microscope to select the region of the sample from which the relevant diffraction pattern is produced, thanks to the diffraction principles operating in elastic

scattering phenomena and employed in other diffraction-based crystallographic techniques, like X-ray diffraction (XRD) and electron backscatter diffraction (EBSD, see ELECTRON BACKSCATTER DIFFRACTION (EBSD)). From these data, the identification of the crystallographic phases present in the specimen can be attained, along with their orientation with respect to each other and to the incident electron beam. The minimum size of the area that can realistically be selected depends not only on the diameter of the selecting aperture, but also on the aberrations associated with the scattering by the edge of the aperture itself, which are increasingly important for lower aperture diameters. Considering that a magnification of $\times 50$, or close to this value, is obtained in the first image plane of conventional TEM, with apertures having minimum diameters of 5–50 μm , a real area not smaller than 0.1–1.0 μm diameter can be selected. Depending on the microstructure of the sample, spot or ring patterns can be attained, as displayed in Figures 2a and 2b, respectively. The first is obtained from one of the aluminum crystalline grains (i.e., single crystal regions) displayed in the TEM micrograph in Figure 2c. The second SAED pattern refers to the nanostructured polycrystalline carbon fibers in Figure 2d.

Diffraction patterns from significantly smaller regions can be acquired, by focusing the incident electron beam on the sample surface using the condenser lens system of the microscope. This operating mode is usually referred to as convergent beam electron diffraction (CBED), useful for crystallographic characterization down to the nanometer scale. Moreover, the fine analysis of the CBED patterns may provide additional information on the sample, like the presence of lattice strain, an accurate estimation of the lattice parameter, and evaluation of the thin foil thickness in the sampled regions (Tanaka and Tsuda 2011). The high coherence of the incident electron primary beam in STEM mode, particularly in field emission gun (FEG) instruments, has disclosed the possibility of recording diffraction patterns from extremely small volumes, with diameters of 1 nm or less (Cowley 2004).

The inelastic interactions of the incident beam with the TEM sample result in the emission of secondary radiations, like X-rays and Auger electrons, and in changes in the energy of the primary

electrons. Since these effects and the intensity of the resulting signals also depend, through specific cross-sections and related parameters, on the concentration of the interacting atomic species, relevant spectroscopies have been developed. The emission of Auger electrons from a TEM thin sample is too weak to be realistically interesting for practical purposes. Energy-dispersive X-ray spectroscopy (EDXS) and electron energy-loss spectroscopy (EELS) are the two techniques more frequently available in TEM instruments. EDXS is based on the electron-induced emission of high-energy X-rays produced by the ionization of the inner electron shells. Since the energies of the emitted X-rays represent a sort of fingerprint of each specific element, the qualitative composition of the analyzed material is the first information that can be easily obtained from this technique. Using correction programs and suitable calibration procedures, often simplified by the availability of virtual standards archives, a quantification of the chemical data is quite straightforward, considering that the so-called “matrix effect”, comparatively more important in the case of SEM bulk samples, can be overlooked in many TEM specimens. In terms of analytical aspects, EELS is particularly recommended for low atomic number elements ($Z < 11$), being in this respect an excellent technique to be integrated with EDXS, which is better suited for higher atomic numbers. For both techniques, a central role is played by the detection systems, which are particularly sophisticated and therefore costly for EELS. EELS detection systems are spectrometers capable of discriminating electrons with different energies, after having interacted with the TEM sample, using magnetic deflection prisms. In this way, it is also possible to select electrons over a narrow range of energies for high-resolution imaging, removing chromatic aberration, and chemical mapping. The electron energy has to be selected close to the absorption edge of the elements to be mapped. Chemical X-ray maps can also be acquired using EDXS coupled to STEM instruments, according to principles and procedures similar to those used in SEM.

The availability of a suitable TEM sample is a prerequisite for any of the above analyses and observations. The most obvious requirement for a TEM specimen is that the region to analyze is electron-transparent. From a practical

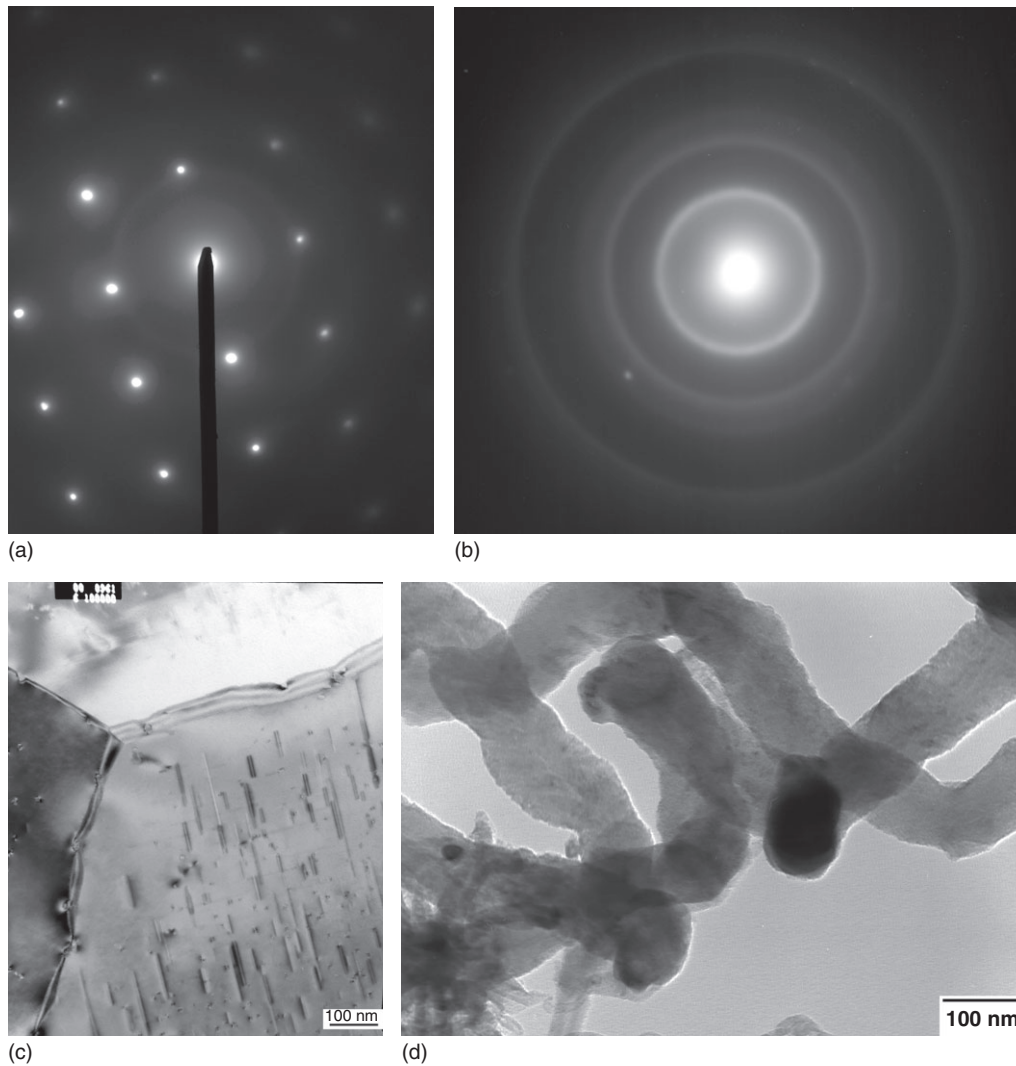


Figure 2 (a) Spot SAED pattern from one of the Al grains displayed in (c). Face-centered cubic crystalline structure. (b) Ring SAED pattern from the carbon fibers in (d). Hexagonal (graphite) crystallographic structure. (c) Al grains. (d) Nanostructured polycrystalline carbon fibers. (Courtesy of Dr Gloria Ischia, University of Trento, unpublished data).

point of view this means that inorganic (metallic alloys, ceramics, glasses, etc.) TEM specimens should have thicknesses in the 10–100 nm range. A greater sample thickness, up to 1 μm or so, is admissible for organic, low atomic number materials, like polymers and biological materials, featuring lower absorption coefficients for electrons. Some samples, like thin films and powders, may already satisfy these transparency

requirements, and therefore they can directly be observed without any thinning procedure. Otherwise, an appropriate sample preparation procedure should be selected, capable of reaching the right electron transparency without altering the genuine, pristine material features. In the case of bulk samples, the first step is a preliminary thinning, based on mechanical cutting, grinding and polishing, to take the specimen thickness

down to 0.1–0.5 mm. For the final thinning, different techniques are available, to be selected on the basis of specific material properties. Metallic materials can be chemically thinned, possibly using electrochemical cells that render the process more controllable and reproducible. Multiphase alloys, ceramics and, in general, ceramic and metal matrix composites can be better thinned using ion-milling, selecting the milling conditions so to avoid, or at least reduce, the effects of ion implantation, radiation damage, or material redeposition. The ultimate evolution of ion-based tools is the focused ion beam (FIB) equipment that can produce ion thinning in a much more controllable way, particularly when coupled with an SEM column (dual beam system) to monitor the thinning in real time and to manipulate the thin foil in the vacuum chamber. This is usually transferred onto a carbon-coated TEM grid, or welded to it for safe transportation, and inserted into the TEM column. This controlled ion-slicing, featuring the additional remarkable advantage of pin-point selection of the interesting part of the sample, may have important advantages for archaeological applications of TEM. Direct cutting of ready-to-observe slices of, mostly, organic and biological samples can be prepared via cryogenic ultra-microtomy. Using mechanical cutting with extremely sharp diamond or glass knives and a very precise positioning system, allowing nanometer-scale displacements, an ultra-microtome can cut thin foils directly from the original bulk sample. Since the slices are extremely delicate, after being cut they are floated onto the surface of alcohol or similar low-temperature freezing liquids, and collected using a standard TEM grid for easy positioning in the TEM sample-holder.

An important practical aspect to consider is the total volume available inside the microscope for each sample. For standard TEM instruments, the whole specimen should fit inside a cylindrical volume, 3 mm in diameter and 0.2–0.3 mm in height. In general, the observable regions will be centered with respect to these dimensions, and this is an additional task that the final thinning technique should be able to accomplish. Of course, it is also important that the interesting features of the archaeological find fit inside the above volume. In general this is not a serious limitation, and actually the high resolution and high sensitivity of

TEM can be exploited to limit to a minimum the size of the sample to be analyzed, which may just consist of fragments mechanically scraped out from the regions of interest, and already feature electron-transparent regions. However, TEM observations, being restricted to comparatively small volumes of a material specimen, require a larger-scale validation of their actual representativeness. In the case of samples with coarse microstructural features, TEM specimens from different pinpointed regions should be sampled accordingly. Moreover, as reported in studies using TEM for the characterization of archaeological finds (see TEM AND ARCHAEOLOGICAL MATERIALS), electron microscopy observations are usually carried out in association with bulk analyses, using optical microscopy (see OPTICAL MICROSCOPY), scanning electron microscopy, X-ray diffraction (see XRD AND MATERIALS ANALYSIS), or X-ray fluorescence (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)) and X-Ray Fluorescence Spectrometry (XRF), which provide an important general framework to the TEM results.

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Vibrational Spectroscopies

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Archaeological objects are mixtures of different chemical compounds. Each chemical compound is unique (it has a given chemical formula that is different from the other compounds) and hence it has unique molecular vibrations (movements among the different elements of the chemical formula). Each vibration has a spectroscopic response in the form of a band at a given wavelength. Such molecular vibrations (the collection of all the spectroscopic bands) are like the fingerprint of each chemical compound. The vibrational spectroscopies are analytical instrumental techniques that measure such molecular vibrations, giving us the spectrum with the different spectroscopic bands (like the fingerprint) of each chemical compound.

Vibrational spectroscopies are techniques to obtain easily the information about the compounds present in any archaeological material, whatever the nature of such compounds: original from the body of the object, newly formed as a consequence of the interaction between the object and the surrounding environment (air, water, or soil), or degraded from the original compound. These techniques can measure powdered materials (around 200 mg) and till spot areas of 1–500 μm on the surface of objects, allowing the possibility to perform macro and micro till analysis.

There are two major vibrational spectroscopies: one based on infrared (IR) radiation as the excitation source, and the other measuring the Raman effect promoted by the excitation of molecules with lasers of different wavelengths. The basis of vibrational spectroscopy techniques, the possibilities for qualitative, quantitative, and classification analyses, and the available databases and search libraries (algorithms) are well described in a recent book (Chalmers, Edwards, and Hargreaves

2012). Currently, IR instrumentation is based on the so-called Fourier transform interferometer (FTIR), while the Raman technique has instruments using Fourier transform interferometers (FT-Raman) but most of them measure the Raman scattering through dispersive Raman spectrometers (Raman as such).

The spectral range of both vibrational spectroscopies is similar. IR spectroscopy covers three spectral ranges: (1) near infrared (NIR) in the 280–2,500 nm range of wavelengths (14,000–4,000 cm^{-1} in wave numbers); (2) middle infrared (mid-IR or simply IR) in the 2,500–25,000 nm (–25 μm) range of wavelengths (4,000–400 cm^{-1} in wave numbers); and (3) far infrared (FIR) in the 25–1,000 μm range of wavelengths (400–10 cm^{-1} in wave numbers). Raman spectroscopy usually covers the 2.5–100 μm range (4,000–100 cm^{-1} in wave numbers). Both spectroscopies have instruments to measure archaeological objects in the laboratory (point-by-point at macro and micro level, or with spectroscopic imaging of surfaces) or use fiber-optic-based probes to measure directly in the field (portable, handheld, remote, and stand-off devices) without the need to take samples from the objects (Chalmers et al. 2012).

IR and Raman spectroscopies are mainly used to identify chemical compounds based on the different spectroscopic responses of the molecular groups belonging to the compound. This identification can be done for organic and inorganic compounds, in crystallized or amorphous forms, and in solid, liquid, or gaseous states. These possibilities of the vibrational spectroscopies offer better performances than other classical analytical techniques applied in archaeology. IR and Raman spectroscopies are not alternative analytical techniques but complementary because some vibrations are not active in IR, others are not Raman sensitive, and others have both possibilities of detection. For example, most metal-oxygen vibrations in oxide compounds are inactive or difficult to detect by IR spectroscopy, while Raman spectroscopy is well suited for such kinds of chemical compounds appearing

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often in archaeological objects. On the contrary, all of the organic compounds (formed by complex molecules with different molecular groups) have both IR and Raman responses, but the IR bands are more selective and sensitive than the Raman ones.

The number of research works and reviews dealing with the use of vibrational spectroscopies to study archaeological objects is increasing continuously. When you type “infrared spectroscopy in archaeology” in the Chemical Abstract database, 413 direct references are displayed and another 1,815 related ones appear. When typing “Raman spectroscopy in archaeology,” the direct number of references increases to 706 while the related references extend to 1,571 research works (data correct as of the end of August 2016). At the beginning, scientific analyses were focused on the characterization of the nature and composition of original materials (stones, organic remains, porous materials, etc.), IR spectroscopy being the analytical technique of choice for standard laboratories working in the field of archaeology; a review (Bacci 2000) included 110 references for works published in the twentieth century on different topics in art and archaeology, and regarding the use of three IR modes: ultraviolet–visible–near infrared (UV-VIS-NIR), FT-IR, and fiber optics reflectance spectroscopy (FORS). When new laser sources became available, Raman spectroscopy started to be the leading spectroscopic technique used in the 1990s (Chalmers et al. 2012), as also observed from the works referred to in the last review published on the use of Raman spectroscopy to identify minerals as the key issue to solve problems in archaeology (Bersani and Lottici 2016).

Analytical techniques and methodological approaches developed in the field of materials science are now widely applied to archaeological objects to gain information about the material composition and structure, to understand the method of manufacturing artifacts, to ascertain the burial influence on the conservation state of the objects, and to identify the stressors that are acting as degradation sources on the objects. In a recent review, Sciau and Goudeau (2015) proposed the study of heterogeneous and complex materials of ancient pottery using an innovative approach by identifying subsystems of materials and applying traditional and novel analytical

methods to scan the whole material at different scales.

One such novel analytical setup is synchrotron-based Fourier transform infrared microspectroscopy (SR-FTIR), a high-level instrumental technique increasingly employed in archaeology. The technique combines the advantages of FTIR spectroscopy with the extra potential of chemical imaging and the properties of the synchrotron source of radiation. The first applications were reviewed some years ago (Cotte et al. 2009), including the fundamental aspects of the IR synchrotron source. More recently, another review has shown the capabilities, advantages, and disadvantages of current and future SR-FTIR spectroscopy, alone or combined with other SR techniques (radiography/microscopy, X-ray diffraction, X-ray fluorescence (XRF), X-ray spectroscopy) to characterize the original materials and degradation compounds in the field of archaeometallurgy (Young 2012).

FTIR imaging started to be used some years ago, with and without the aid of SR sources. Since 2010, several research works have described the fundamental aspects, accessories, and applications in both micro- and macro-attenuated total reflectance (ATR) imaging, covering the applications of both imaging techniques to, among others, archaeological and other heritage objects. Some recent works also used not only the mid-IR spectral region but also the NIR one to increase the capabilities of the different modes of IR spectroscopy.

The possibilities of IR have been extended with the introduction of commercially available portable/handheld instruments, working in three modes. One uses the contact capabilities of FORS to measure the reflectance of illuminated samples in the mid-IR region, focusing IR radiation vertically through an optical fiber and collecting the reflectance also vertically through a second fiber; the disadvantage of this configuration is the interference produced by the specular reflection in some samples. The second is known as diffuse reflectance infrared Fourier transform spectroscopy (DRIFTS), working in the mid-IR range, also a contact portable device where the two optical fibers are positioned at different incident angles in the head of the instrument, allowing reduction of the effect of the specular reflection to only one principal IR band; with this

system (and also with FORS) the identification of compounds must be done using the secondary and combination IR bands, an effective practice although not used when working with other FTIR systems (transmission/absorption or ATR) where the identification is based on the main IR bands. The third mode measures NIR reflectance in a stand-off mode (at distances greater than 1 m), promoted by illumination of the sun on the archaeological objects.

The first work using Raman spectroscopy in this field was published in 1984 using a Raman laser microprobe to analyze the pigments of painted manuscripts and archaeological materials. Since then, Raman microscopy and Raman microprobe modes have been extensively used throughout the last century to characterize materials (archaeological and historic ceramics, Roman intaglios, pre-Spanish ceremonial gemstones, pigments of pre-historic rock art paintings, Roman mural paintings, etc.) but also to ascertain past technology for manufacturing archaeological Egyptian blue and green pigments. With the advent of the new century, the number of research groups using Raman spectroscopy increased, and consequently new findings were published, covering not only the characterization of original compounds in archaeological objects but also the nature of degradation products (efflorescence crystals, biofilms, unexpected compounds on the surfaces of excavated materials, etc.), that were not previously described, the influence of environmental conditions on the conservation state of the objects, and some new strategies in the conservation of the objects.

Most of these new findings have been presented in the biannual edition of the International Congress on the Application of Raman Spectroscopy to Art and Archaeology (RAA series), which started in 2001. The eight editions of this dedicated congress is a measure of the current importance of Raman spectroscopy in archaeological research. Some of the contributions are selected to be published as peer-reviewed papers; these contributions can be found by searching the references collected in the editorial of the last edition (Ropret and Madariaga 2014).

From the first edition, the importance of the development of a mobile Raman system was clearly seen. The historical developments of such spectrometers to perform field analysis

are detailed in references 4–14 of the review by Bersani and Lottici (2016). Nowadays, most of the instrumental companies in the field of Raman spectroscopy offer mobile systems, from portable to handheld devices, working with one (1,064, 785, and 532 nm) or two lasers as excitation sources, and with different resolutions and sensitivities. Now we have commercially available portable spectrometers with better performance than the standard laboratory instruments of the past century. These facilities give us the possibility to go directly to the settlements and perform high-level research directly in the field.

One important property of some chemical compounds is the change to different chemical forms (different molecules in practice) with temperature. For example, in the family of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) this compound is stable from ambient temperature to 45 °C. If the object containing gypsum is heated up to this temperature, the compound dehydrates to bassanite ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$), which is stable in the range 45–110 °C. If the heating process continues, the next compound is anhydrite type III ($\gamma\text{-CaSO}_4$, hexagonal), a soluble phase stable between 110 and 300 °C; then it becomes anhydrite type II ($\beta\text{-CaSO}_4$, orthorhombic), an insoluble and stable phase in the range 300–1,180 °C; and finally the end member of this family is anhydrite type I ($\alpha\text{-CaSO}_4$, cubic), the most insoluble and stable phase at temperatures higher than 1,180 °C. These compounds have different Raman spectra, giving us the option to have an indirect thermometer analyzing the spectrum of the sample. Thus, if we detect only the presence of anhydrite type II, this means that the sample has never reached the temperature of 1,180 °C. In some cases, mixtures of two spectra of the same family are found; using a mathematical tool, the spectrum is decomposed using the sum of XX percent of compound-1 plus YY percent of compound-2 (with $\text{XX} + \text{YY} = 100\%$) and this is used to provide a better estimation of the temperature; thus, if we have 70 percent bassanite and 30 percent anhydrite type III, this means the object has reached around 120–130 °C.

The thermal properties and associated Raman spectrum of different mineral phases that can be used as indirect thermometers are detailed in the review by Bersani and Lottici (2016), including examples applied to ceramic, lapidary

objects, archaeological gemstones, and mineral pigments. In the particular field of archaeological and historic ceramics, the change of the Raman spectrum as a function of temperature has been largely exploited to ascertain the firing conditions of manufacture, as well as those of the glazed decorations on such objects; some examples and references of the possibilities offered by Raman spectroscopy in this field are also included in the review by Sciau and Goudeau (2015) and the book by Chalmers et al. (2012).

Changes in the original compounds start at the moment of burial of the object. This burial is usually done by sediments (soil particles in very wet conditions), and, with time, the amount of such sediments increases and, in practice, soils appear on the top. Such soils can be natural (plants and grass covering the outermost layer) or cultivated (farming with natural or chemically amendment products). These soils are continuously washed by the rain that incorporates ions taken from the atmosphere, especially CO_2 , an acid compound when dissolved in water (carbonic acid, H_2CO_3) with a high chemical reactivity. If the archaeological settlement is in an area with a polluted atmosphere, other chemicals like sulfates, nitrates, and light carboxylic acids will be dissolved in the rainwater; if the settlement is near a coastal area, the marine aerosol (chloride, sulfate, sodium, magnesium, etc.) is always incorporated in the rainwater. When these waters percolate (vertical displacement of the waters through the soil layers) the initial dissolved ions are enriched by dissolution of the compounds present in the top of the soil; in this case, special attention must be paid to ammonium nitrate (NH_4NO_3)—a salt always present that has an acid in the cationic side (NH_4^+) and in the anionic side a harmful compound (NO_3^-) from the conservation state point of view.

Depending on the nature of the atmosphere and the soils of a particular settlement, the dissolved ions and compounds in the rainwater reaching the archaeological objects can be very significant. These ions can start interacting (by chemical reactions) with the compounds originally present on the surface or in the bulk of the objects, leading to a very complex set of new chemical compounds that compromise the conservation state of archaeological objects when excavated. Fortunately, Raman spectroscopy is

sensitive enough to detect such new chemical compounds (the decaying products), being the analytical technique of choice to diagnose the conservation state of excavated objects.

A multidisciplinary work performed by archaeologists, museum restorers, and chemists (Veneranda et al. 2016) is a good example of the current possibilities of research. The aim was (1) to characterize the conservation state of copper-based alloys (several buckles) and iron-based (one spur) medieval objects found in an excavation at only 20–40 cm depth, in a settlement at 400 m above sea level but with the direct influence of marine aerosol, and (2) to ascertain which chemical reactions took place on the objects to explain the formation of the corrosion compounds. First, the soils were characterized, especially the soluble ions present. Second, the corrosion compounds (vibrational spectroscopy techniques are not sensitive to metallic elements like copper and iron) were identified in both kinds of objects using two portable Raman spectrometers (using 785-nm and 532-nm excitation lasers). A key corrosion compound, akaganeite (an iron hydroxide with chloride inside), was detected that conditioned the election of the conservation procedures in the museum in order to minimize the influence of chlorides (this particular compound cannot be detected by IR spectroscopy). Finally, the authors were able to ascertain the chemical reactions promoting the formation of all the detected corrosion compounds, identifying the impact sources affecting the archaeological objects. In this work, other analytical techniques were used, complementing the information obtained by Raman spectroscopy.

The use of other analytical techniques to complement the vibrational spectroscopic information is a clear trend in the future (see Further Reading). As an example of this trend, another multidisciplinary work can be cited (Hernanz et al. 2014 and supplementary information) where archaeologists, chemists, geologists, conservators, environmental managers, and heritage managers worked on five rock-shelters with significant examples of the Levantine and schematic rock-art of the Iberian Peninsula. First, field analyses were performed with portable Raman and DRIFT spectrometers, selecting microsamples of interest to perform further analyses in the laboratory

using Raman microscopy and Raman imaging, all vibrational spectroscopic techniques. The work describes well the measurement constraints when using micro-Raman spectroscopy in the field and how these can be overcome. The results were complemented with portable (XRF) and laboratory (scanning electron microscopy coupled with energy dispersive spectroscopy (SEM-EDS)) instruments for elemental analyses, obtaining the same picture for the different pictographs: the painted layer is over a series of geological layers and above another set of layers naturally formed hundreds of years after the painting process.

SEE ALSO: Conservation; Deterioration; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Pollution and Heritage Conservation; Raman Spectroscopy; Soil Chemistry in Archaeology

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X-Ray Absorption Spectroscopy (XAS, EXAFS, XANES)

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Introduction

Synchrotron photon-based methods (see SYNCHROTRON-BASED X-RAY ANALYTICAL TECHNIQUES AND MATERIALS ANALYSIS) are increasingly being used for the physico-chemical and structural study of ancient and historical materials (e.g., in archaeology, conservation sciences, paleontology, etc.). Parameters such as the high photon flux, the small source size, and the low divergence attained at the synchrotron make it a very efficient source for a range of advanced spectroscopy and imaging techniques, adapted to the heterogeneity and great complexity of the materials under study. Among the synchrotron-based X-ray methods, X-ray absorption fine structure spectroscopy (XAFS) has been relatively recently applied to heritage studies, and it is now widely used since it offers a combination of features particularly well-suited for the study of rare, ancient materials and works of art (Quartieri and Arletti 2013; Farges and Cotte 2016). XAFS techniques—including pre-edge, X-ray absorption near-edge structure (XANES) and extended X-ray absorption fine structure (EXAFS) regions—are non-invasive, have low detection limits, afford high lateral resolution, and provide exceptional chemical sensitivity. They can be applied in air and have virtually no restrictions on the type and size of the sample, they are applicable to most of the elements of interest, even at very low concentrations, and, finally, to a wide variety of materials, ranging from hard matter such as glass, ceramics, and metals, to softer materials such as paintings, bone, wood, and paper. All these characteristics are highly

desirable for the scientific investigation of precious, heterogeneous, and complex materials. In particular, the chemical mapping capability, with high spatial resolution that provides information about local composition and chemical states, even for trace elements, is a unique asset.

The XAFS studies of cultural heritage in general aim to understand (1) the geographical provenance and original fabrication processes, and/or (2) the degradation reactions undergone by the ancient materials. The former mostly concerns the craftsman's control over synthetic reactions at high temperature, resulting in various optical effects in glasses, glazes, lusters, ceramics, and pigments. The latter—more concerning paintings, bone, wood, and paper—occur over longer timescales and are either due to past conservation treatments or due to passive external circumstances, or may even be an inherent part of the chemical composition of the artwork itself.

Basic principles of XAFS and experimental approaches

X-ray absorption spectroscopy (XAS) techniques are based on the measurement of the variation in the absorption coefficient while scanning the incident X-ray photon energy in a narrow region around an absorption edge (Figure 1). This variation is physically related to the excitation cross-section of the core electrons into unoccupied electronic states or into the vacuum continuum. The spectral features observed close to the absorption edge, referred to as X-ray absorption near-edge structure (XANES) (Figure 1), depend on the local molecular environment (oxidation state, coordination numbers, site symmetry) of a given absorbing atom, and also provide the basic mechanism for imaging with chemical specificity. The extended X-ray absorption fine structure (EXAFS) signal is measured when the energy of the incoming X-rays is scanned far beyond the absorption edge of interest. Constructive and destructive interference between the outgoing and backscattered photoelectron waves results

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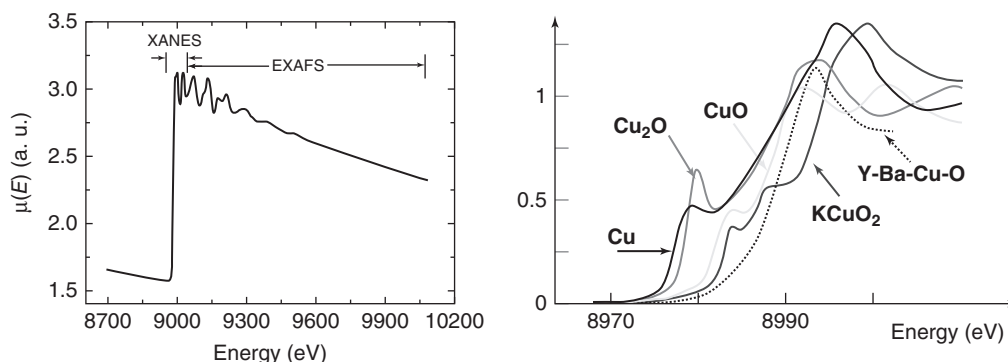


Figure 1 Left: XAFS K-edge signal of crystalline copper; XANES and EXAFS regions are indicated. Right: Dependence of the Cu K-edge XANES spectrum on the copper oxidation state.

in EXAFS oscillations. The analysis of these signals provides information on the identity of the surrounding atoms, specific bond distances, and coordination numbers.

Due to the high absorbance of most materials encountered at energies below 20 keV, most X-ray absorption experiments in the fields of archaeology and Cultural Heritage (CH) are performed using XANES in fluorescence detection mode, by collecting the signal typically over some tens of electron-volts. The XANES fingerprint obtained is interpreted by comparison with a number of reference compounds.

Interestingly, during these experiments, spot spectra can be collected with typical beam diameters from a few hundreds down to a few microns—referred as μ XANES and μ EXAFS measurements—and combined with other X-ray microbeam-based techniques, such as μ -fluorescence analysis or imaging. These multi-technique approaches have proven their value over more conventional combinations of methods, especially for the study of highly heterogeneous or decorated samples, and for the characterization of degradation products that are formed in thin layers at the surface of weathered archaeological and/or artistic materials and artifacts. Actually, since both degradation and fabrication processes (selected raw compounds, production reactions, temperature, atmospheric conditions, etc.) are usually based on oxidation–reduction reactions, XANES analysis is a powerful tool to understand the life and evolution of art materials.

Elements and materials

Although XAFS techniques can be applied to almost all of the chemical elements of the Periodic Table, not all are equally studied. Fe and Cu clearly attract major attention. The main reason is their almost ubiquitous presence in artistic materials and coloring properties, being in pigments (see CHARACTERIZATION OF PIGMENTS), inks (see INK), but also glass or metallic artifacts (see CHARACTERIZATION OF METALS AND ALLOYS). Similarly, Mn is present in various natural mineral or biogenic pigments, as well as in glasses.

These elements, being transition metals, are chromophores, and their electronic state is usually responsible for the optical appearance of artworks. In addition to other heavy metals such as Cr, Ag, Sn, and Sb, they are increasingly analyzed by XAFS techniques to gain new insights into the chemical origin of color and of optical effects, in particular in glasses and ceramics, such as opacity, iridescence, metallic luster, and shine. As aforementioned, XAFS techniques are extremely suited for the analysis of such materials because, being based on short-distance probes, they can be equally applied to crystalline and amorphous samples. When performed in fluorescence mode, the selective analysis of minor diluted elements is possible, even in complex mixtures. Indeed, the above-mentioned optical effects are frequently obtained by introducing small quantities of these chromophores.

On the other hand, an increasing number of works aim at understanding the evolution of

these materials with time (degradation, corrosion, paper aging—see PAPER ANALYSIS). For instance, problems caused by alteration in paintings, metals, or wood (see DETERIORATION OF WOOD) have been investigated by many experiments conducted at the S and Cl K-edges. These elements can have an exogenous origin, and XAFS enables us to determine their influence on the artistic materials (Bertrand et al. 2012).

Selected examples of XAFS heritage studies

The goal of the entry is to illustrate, not exhaustively, some of the main applications of XAFS to heritage objects. Most of the examples here selected, and many others of great interest to archaeologists, curators, conservators, and art historians, are reported and discussed in the reviews cited in the introductory section.

Archaeological and stained glass

XANES and EXAFS techniques were first applied to *ancient glass*, and thanks to the peculiar characteristics of these methods, they are presently widely used to study non-crystalline ancient materials. Recent reviews of this topic and of the correspondingly rich literature are provided by Quartieri and Arletti (2013), and Farges and Cotte (2014). Interested readers are invited to consult the bibliographic references cited therein.

The first pioneering work was by Nakai et al. (1997), who performed a XANES study on glass samples and ceramic sherds excavated from a site in Turkey, providing information on the chemical nature and on the oxidation state of the colorant elements. Actually, most XAFS applications to historical glass research have been devoted to interpreting the origin of the artifact's color. Scientific analysis on this topic may provide important information on the ancient production technology and on the selection of ingredients responsible for color and opaque effects.

The color exhibited by glass (see GLASS COLOR) can depend on the oxidation state and the electronic configuration of the constituent metal ions. These are usually elements belonging to the transition row of the Periodic Table that, when

undergoing d-d electronic transitions, absorb characteristic frequencies of the visible light spectrum. Concerning opaque vitreous glass and vitreous mosaic tesserae, the color and opaque effects were obtained by means of many different substances (i.e., calcium and lead antimonates, lead stannate, tin oxide, quartz, wollastonite, metallic clusters), depending on the age and on the desired effects. In particular, regarding ancient red glass, color and opacity are generally ascribed to the presence of copper of different speciations (metallic clusters, or cuprite dendritic aggregates, or cations incorporated in the glass matrix).

Another ubiquitous element in archaeological and artistic glass is iron. It is typically present at levels that can impart, when in the reduced form, a well-known green coloration. To minimize this problem and to obtain transparent uncolored glass, from around the middle of the first millennium BCE, substances were added which tended to neutralize the effects of iron and/or to confer different colors. The main decolorant used before the Roman period was antimony oxide, while, from the second century BCE, manganese oxide was more frequently used. The coloring and decoloring roles of Fe^{2+} and Mn^{4+} , respectively, and their redox interactions during glass production, is central to a number of studies performed by XAFS. For instance, the Fe and Mn K-edge XANES spectra of a suite of transparent fragments of perfume bottles of the second century CE from Patti Villa, Sicily, were recorded. All finds contain both iron and abundant manganese, with the exception of one sample, characterized by a bottle-green color, which is lacking in manganese. The detailed analysis of the XANES features and of the pre-edge peak structure of the samples and a series of reference compounds revealed that, in the uncolored ancient glasses, iron is always present mainly as Fe^{3+} , while manganese is present in the reduced form Mn^{2+} , validating the hypothesis of a redox interaction between iron and manganese ($\text{Fe}^{2+} + \text{Mn}^{4+} \rightarrow \text{Fe}^{3+} + \text{Mn}^{2+}$), as a result of a deliberate addition of pyrolusite as a decolorant during the melting procedure.

In studies on historical glass and archaeological glass, the problems related to *weathering* are of paramount interest. They are faced by means of XAFS, especially on stained and buried glass. Stained glass, like for instance ancient cathedral windows, have been exposed for many centuries

to open air, atmospheric particulates from urban environments (diesel particles, dusts enriched in sulfates from combustion of wood, coal, candles), mold (when water condenses) as well as oceanic salts when they are exposed to coastal influences. Archaeological glasses are usually found buried in sepulchres (or in sunk vessels) and are exposed to chemical and microbiological interactions in soils or corrosive seawater.

Information on these artifacts is then essential to curators in order to conserve them. One of the first investigations on stained weathered glass windows was that on the St Gatien cathedral in Tours, France (thirteenth to fifteenth centuries). This cathedral is exposed to the oceanic climate from the Gulf Stream, and its stained glass windows (fourteenth century) show light brown corrosion cupules on the glass surface oriented to the inside, whereas thick, weathered white-greenish layers are visible on the outside surface exposed to atmospheric agents. In cross-section, these glasses consist of a 500 μm -thick layer composed of micron-thick layers of deep red and pale-green glasses. But the thin red layer is so intense in color that it gives its red color to the whole glass. Cu K-edge μ -XANES and EXAFS experiments have shown that the red color for some of these glasses is due to metallic copper nanoparticles (see NANOARCHAEOLOGY). In contrast, Cu is divalent in the weathered pale brownish-greenish crusts, with a local structure similar to that for chalcantite ($\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$).

A further proof of the importance of XAFS in cleaning and restoration interventions is provided by a study by Cagno et al. (2011) who, thanks to Mn K-edge μ XANES experiments, monitored the effect of a surface treatment of severely darkened birnessite-rich medieval glasses with a solution that solubilizes Mn(IV) into Mn(II). Negative side-effects of these treatments were revealed, including thinning of the glass upon crust removal.

Pigments and paintings

A large number of XAFS experiments focus on the speciation of archaeological and historical pigments and paintings, and on the characterization of their degradation reactions (Farges and Cotte 2016; Janssens et al. 2013).

Let us first discuss the interesting case of Paleolithic pigments. Since the discovery of cave rock art throughout Europe, several questions have been raised regarding the geographical and geological origins of the pigments used during the Paleolithic period, as well as the preparation and painting methods. The red color is systematically due to hematite ($\alpha\text{-Fe}_2\text{O}_3$), yellow to goethite ($\alpha\text{-FeOOH}$) or related ochre compounds and, finally, black to charcoal or manganese oxides/hydroxides. Chalmin and co-authors (2007) have identified various manganese oxides in black pigments, such as pyrolusite and romanechite, as well as other rare ones like manganite and groutite in various Paleolithic caves in Spain and France, including Lascaux. The use of XAFS in this study was needed because of the small size of the samples and because many samples were cryptocrystalline. Very interestingly, massive and fairly pure manganite was found in the cave of Combe-Saunière in the Dordogne, France. The sample, a sort of “crayon”, is thought to have served as a “pen” for the frescoes painted by those Paleolithic artists. Since this mineral is rare in nature and unknown in the areas where these paintings were realized, some trading routes must have existed to explain its presence in the Dordogne area.

Another important application of XAFS regards the *degradation phenomena* occurring in artistic pigments and paintings. Pigment degradation is usually a superficial phenomenon, where the major elemental composition remains unchanged, but where oxidation or reduction affects the chemical environment of elements, and consequently the color of pigments. μ XANES, which probes the element speciation with very good sensitivity and with submicrometric resolution, is particularly relevant for such analyses. Janssens and coworkers (2013) presented an exhaustive report of the μ XANES analysis of pigments over the last few years, and many other examples have been discussed by Farges and Cotte (2016) and Bertrand et al. (2012). For instance, XAFS has recently been used to study the fading of Prussian blue, the discoloration of smalt, the darkening of lead chromate in Van Gogh paintings, as well as in artificially aged model paintings. In this last case, it was shown

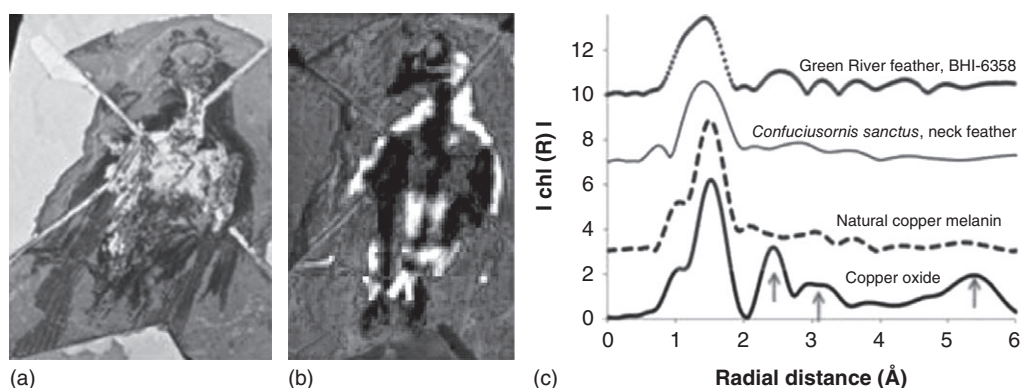


Figure 2 (a) An optical image of *Confuciusornis sanctus*. (b) Synchrotron rapid scanning X-ray fluorescence false-color images of the MGSF315 main slab. White: Cu; Black: Ca; Gray: Zn. (c) Radial distribution functions from EXAFS analysis at the Cu K edge of two standards compared with fossil feathers. The arrows in the copper oxide standard spectrum indicate features that are not present in the eumelanin standard. Modified after Wogelius et al. (2011), published by the American Association for the Advancement of Science.

that in both original and artificial painting fragments, pigment darkening was linked to the reduction of chromium from Cr(VI) to Cr(III).

Paleontological findings

The study of fossil remains and ancient human artifacts provides a wealth of information on ancient societies or cultural events and, more generally, can explain how systems or organisms adapted and evolved over time. One of the major problems encountered during the analysis of rare and ancient paleontological specimens derives from the fact that many analytical tools destroy at least part of the object under study. In this regard, micro-beam synchrotron-based techniques can be very powerful tools for non-destructive investigations.

In a recent study (Wogelius et al. 2011), synchrotron X-ray techniques—including XAFS—were applied to the study of fossils and extant organisms, including *Confuciusornis sanctus*, in order to map and characterize possible chemical residues of melanin pigments in extinct bird feathers. Figure 2a shows a visible light image of one of the *C. sanctus* specimens analyzed. Figure 2b presents the distribution of the key trace metals Cu, Ca, and Zn within this specimen as a false-color intensity map. The detail revealed in the distribution of Cu is striking, and

strongly implies that the Cu zoning is endogenous. Moreover, full EXAFS analysis of the Cu in the *C. sanctus* feather regions indicates that the element is organically bound, closely resembling the coordination environment found for Cu in natural melanin pigment (Figure 2c).

SEE ALSO: Archaeometry; Characterization of Metals and Alloys; Characterization of Pigments; Deterioration of Wood; Glass Color; Ink; Nanoarchaeology; Paper Analysis; Synchrotron-Based X-Ray Analytical Techniques and Materials Analysis

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X-Ray Fluorescence Spectrometry (XRF)

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X-ray fluorescence (XRF) is now a well-established method of analysis in both the laboratory and industry. The fact that the method is essentially nondestructive makes it particularly attractive for the analysis of archaeological and museum artifacts. Due to certain fundamental characteristics of the technique it is not suitable for some projects, which would seem at first sight to present no problems (Hall 1960).

Edward Hall's abstract for his 1960 paper entitled *X-Ray Fluorescent Analysis Applied to Archaeology* in the journal *Archaeometry* is just as appropriate more than half a century later. XRF spectrometry may be more "well established" but is still "not suitable for some projects," even though it might seem so and archaeologists might want XRF to be so. This section is dedicated to a brief discussion of the applicability of XRF analysis in archaeology.

How does XRF work and, more importantly, when and where is it appropriate? A number of recently published works delve into the subject in great depth and are highly recommended for further edification (summarized in Shackley 2011a).

Today, the market is being flooded with, it seems, hundreds of portable X-ray fluorescent (pXRF) instruments (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)), but do they really do all that the marketing suggests (Shackley 2011b)? Ioannis Liritzis and Nikolaos Zacharias provide a critical evaluation of pXRF in obsidian studies as well as other archaeological materials (Liritzis and Zacharias 2011). Is there a need anymore for the desktop/laboratory energy dispersive X-ray fluorescence spectrometry (ED-XRF)? Can we as archaeologists get away with only a much less expensive pXRF? Observing as an academic in a major university, upcoming students showed an increasing interest in pXRF as a solution to a

problem—is it a solution looking for a problem, or a very real need to be able to carry great analytical power into remote field conditions or museum settings? It may, indeed, be too soon to definitively answer these questions, but very recent newer versions of pXRF instruments and software may be resolving some of these issues.

The vast majority of archaeological XRF world-wide is applied to inorganic materials, mainly volcanic rocks (see ARCHAEOLOGY), and there are very good technical reasons for that (Shackley 2011a). This does not mean, of course, that there are not perfectly good reasons for analyzing ceramics or organics. While pottery is "not a rock," it is composed of rocks and clay sediments that lend themselves to XRF analysis. The very real difference is that unlike volcanic rocks as an example, they are not formed at very high temperatures in the mantle or crust, and may not necessarily be a reflection of human production.

What is very different from Hall's XRF world in the early 1960s is that archaeology as a discipline has changed markedly, both theoretically and methodologically, due in large part to the tools and technology that are offered in the twenty-first century. Issues of social identity, equality, gender, national character, and native rights are all current and important issues in archaeology today, and are being addressed with these new tools—XRF certainly among them (Joyce 2011). Scholars have argued elsewhere that without our twenty-first-century archaeological tools, a twenty-first-century archaeology would be not much more than the New Archaeology of the 1960s or culture historical in nature (Joyce 2011). XRF spectrometry will play an important role as a "well-established method" for illuminating our ever-changing problems in archaeology well into this century. What XRF will look like in another 50 years is impossible to imagine. The portables are probably a peep into that future.

History of XRF

X-rays were first discovered by the German physicist Wilhelm K. Röntgen (1845–1923), for

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which he won the Nobel Prize in 1901. Charles G. Barkla in 1909 found a connection between X-rays radiating from a sample and the atomic weight of the sample. In 1913, Henry G. J. Moseley helped number the elements with the use of X-rays, by observing that the *K* line transitions in an X-ray spectrum moved the same amount each time the atomic number increased by one, a primary theoretical precept in XRF physics. He is credited with revising the periodic tables that were based on increasing atomic weight, to periodic tables based on atomic number. He later laid the foundation for identifying elements in X-ray spectroscopy by establishing a relationship between frequency (energy) and the atomic number, a basis of modern X-ray spectrometry. The potential of the technique was quickly realized, with half of the Nobel Prizes in physics awarded to developments in X-rays from 1914 to 1924. The early natural scientists could never conceive of the advances in XRF instrumental technology we enjoy today.

Principles of XRF

In ED-XRF analysis, samples are irradiated with high-energy photons from an X-ray tube or radio isotopic source. The primary X-ray beam excites electrons in the sample, causing it to emit secondary X-rays, that is, to *fluoresce* during a return of electrons to their orbits. The emitted X-rays occur at energies specific to elements in the sample, appearing as peaks over a given energy spectrum. The height or *intensity* of a given peak reflects, in part, the concentration of that element in the sample, and may be converted to units of concentration, usually by comparison to a regression line based on well-characterized standards after detection (Shackley 2011b).

Traditional destructive XRF analysis of geologic samples requires rigorous and time-consuming sample preparation. Samples are ground to a fine powder and pressed into briquettes, or for analysis of major elements to provide homogeneity, prepared as fused glass disks, particularly for wavelength XRF (W-XRF) where the relationship between the angle of the instrument and the object analyzed is crucial. However, with ED-XRF where the emitted

energy is captured by the detector for all elements simultaneously, and directed to a multichannel analyzer converting energy to pulses and ultimately through software to elemental data, the surface of the object is not as critical, and samples can be analyzed whole (Davis et al. 2011). While early ED-XRF instruments did not yield the instrumental precision of W-XRF, certainly neutron activation analysis (NAA) (see NEUTRON ACTIVATION ANALYSIS (NAA)) and advances in detector electronics and software have decreased the difference between these instruments and with miniaturization have heralded the pXRF emerging technology (Lirtizis and Zacharias 2011). A number of experiments (summarized in Davis et al. 2011) have shown that ED-XRF is *the* best technique in the analysis of volcanic rocks when sample destruction is not possible.

The overarching assumption seems to be that XRF, particularly ED-XRF, solves so many of our problems in geoarchaeology. Glascock (2011) addressed this issue by directly comparing the results of NAA with ED-XRF for obsidian sources (see CHERT, SILEX, AND OBSIDIAN SOURCING) of Mexico. See that study for an in-depth discussion on this subject.

What XRF can do

The appeal of X-ray analysis of archaeological specimens lies in its remarkable combination of practical and economic advantages:

- **Nondestructive:** In the vast majority of cases, analyzed samples are not destroyed or changed by exposure to X-rays. They can thus be saved for future reference or used for other types of testing that may be destructive, such as obsidian hydration analysis (see OBSIDIAN HYDRATION DATING).
- **Minimal preparation:** Many samples can be examined with little or no pre-treatment, including almost all obsidian artifacts. While it is best to wash any sediments off archaeological specimens, it has been shown that if the sediment is minimal, and the artifact has not been subjected to heat so high as to melt some sediment matrix onto the sample, vigorous cleaning is not necessary (Shackley and Dillian 2002). This is mainly due

to the penetration of X-rays in the mid-Z X-ray region beyond the surface, and while it does incorporate any contamination on the surface it is generally not an issue if some soil remains in the flake scars. The analyzed volume is very large compared to any surface contamination. This is not the case with most metals (see CHARACTERIZATION OF METALS AND ALLOYS), where patination and chemical weathering can radically change the composition at the surface and yield erroneous results (Hall 1960).

- Fast: X-ray spectrometry enables chemical compositions to be determined in seconds. For analysis of the elements Ti-Nb plus Pb and Th on the Berkeley Thermo desktop instrument at 100 live seconds per sample it takes about three to four minutes per sample to process, depending on mass.
- Easy to use: Modern instruments run under graphical interfacing software that easily handles measurement set-up and results calculation. Tasks that once required the constant attention of a trained analyst can now be handled by skilled students and are fully automated.
- Cost effective: Without the more involved sample preparation necessary in most W-XRF and all destructive analyses, the cost is significantly lowered per sample.

While this suggests that XRF will solve all our problems, it is not the all-knowing black box we would like it to be.

What nondestructive ED-XRF cannot do

- Sample size limits: Samples > 10 mm in smallest dimension and > 2 mm thick are optimal for ED-XRF analyses (Davis et al. 2011). Why is this important? Eerkens et al. (2007) noted that for hunter-gatherers in the North American West, high residential mobility often requires that stone sources, including obsidian, be conserved for long periods of time. As an example, an archaic hunter will attempt to rejuvenate a dart point rather than make a new one whenever possible as he or she moves through the landscape. The rejuvenation of that point creates debitage

that is quite small, often smaller than 10 mm. With modern recovery techniques, small debitage is recovered much more often than they were in the past, and to make a long story short, Eerkens et al. (2007) found that indeed these small obsidian flakes in Great Basin sites indicated not only greater distance to the original tool raw material, but also a greater diversity of sources than visible with analysis of the larger flakes with ED-XRF. So, while ED-XRF can analyze much of the stone material left in prehistory, it may not solve all problems of interest to twenty-first-century archaeologists. To be fair, however, the procurement ranges that could be reconstructed were relatively accurate with samples above the 10-mm threshold in the Eerkens et al. (2007) study, and NAA had to be used on the smaller flakes, which is essentially a destructive technique. Recently, however, with the newer digital ED-XRF instrumentation and tube collimation we have been able to reach sizes down to 2 mm with the Thermo Scientific Quant'X ED-XRF at Berkeley and Albuquerque.

- Restricted elemental acquisition: As discussed below, nondestructive XRF is restricted generally to a subset of the mid-Z X-ray region, and the best portion, including Ti-Nb, contains excellent incompatible elements for the analysis of volcanic rocks (Shackley 2011b). While some rare earth elements and those with low atomic numbers or with very low concentrations can be useful in discriminating sources, in most cases XRF cannot solve that problem. This is discussed in detail in Glascock's comparison between XRF and NAA (2011).
- XRF cannot characterize small components: XRF like NAA is a mass analysis—every component in the irradiated substance is included in the analysis. It is possible to collimate the incoming X-rays from the tube and/or into the detector to focus on small components such as various minerals, but environmental scanning electron microscopy (E-SEM), electron microprobe, or laser ablated inductively coupled plasma mass spectrometry (LA-ICP-MS) (see MASS SPECTROMETRY (MS)) is much better suited to this kind of analysis. However, the bulk

analysis of volcanic rocks has shown to be quite effective.

It is true that XRF will not solve all our problems in archaeological provenance studies; it is simply the best nondestructive analytical tool at our disposal at this time.

Is pXRF just the latest development in XRF?

While pXRF has both become very popular and been highly criticized, this is to be expected in a discipline that borrows much of its analytical technology (Liritzis and Zacharias 2011; Shackley 2011a, b). What seems to be most problematic is that these portable instruments were originally designed for mining and industrial applications seeking only qualitative results. This is not necessary and sufficient to address archaeological problems where relatively precise quantitative data are required. Tied to this, most of the instruments, unlike laboratory/desktop ED-XRF, did not allow the user to generate their own calibrations; indeed, most relied solely on fundamental parameter routines that are often standardless and could not be modified beyond factory settings. The criticisms have had their effect, and many of the manufacturers are generating software that allows the user to employ linear calibrations by ratioing peaks/counts to the Compton scatter and thus eliminate the problem of differing sample sizes, as earlier discussed by Davis et al. (2011) for laboratory ED-XRF instruments. Given these important shifts in the ability of pXRF, it will be possible to take a sensitive instrument to field or museum settings and nondestructively analyze at least volcanic rocks with similar instrumental precision and accuracy as laboratory XRF instruments. Most of the pXRF systems now available do not acquire the range of elements that laboratory systems do (i.e., Na through U), but the mid-Z (i.e., $Z = 19\text{--}41$) element sensitivity seems to be very good. There may come a time in the near future when portable systems will acquire the typical Na through U elements that laboratory instruments can today, but it is not here yet. This is likely the future of XRF in archaeology.

Hopefully, archaeologists will evaluate it with the same skepticism that is healthy for the discipline.

SEE ALSO: Characterization of Ceramics; Chemistry in Archaeology; Elemental Analysis of Pottery; ICP-MS and Material Analysis; INAA and Material Analysis; Volcanic Rock Sourcing; XRD and Materials Analysis

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X-Ray Photoelectron Spectroscopy (XPS)

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X-ray photoelectron spectroscopy (XPS), also known in former times as electron spectroscopy for chemical analysis (ESCA), is one of the most popular surface analytical techniques applied to archaeology (see [ARCHAEOLOGY](#)) and archaeometry (see [ARCHAEOMETRY](#)). It is a surface-sensitive technique that provides the chemical state and composition within a sampling depth that might be estimated between 3 and 10 nm depending on the material and on the instrument geometry. Soft X-ray beams, usually Al K α (energy = 1486.6 eV) or Mg K α (energy = 1253.6 eV), are used as sources, the monochromatic Al K α source allowing the achievement of high-spatial resolution (down to 3 μ m) and high-energy resolution (0.45 eV).

If the sample size fits the XPS sample holder, no particular sample preparation is required and the sample can be analyzed in the as-received state. With modern spectrometers, many samples at once can be mounted on the platen. Analysis of powders and of low-vapor tension liquids is also possible. Sample treatments in situ include heating up to about 750 °C, cooling down to the liquid nitrogen temperature (ca. -170 °C), cleavage of minerals, and argon ion sputtering.

Since XPS is a surface-sensitive technique, the presence of an organic contamination layer, which might be quite thick in old artifacts, may mask the signals coming from the material underneath. In such cases it might be difficult to obtain the chemical information, and a surface cleaning procedure might be necessary either with solvents or by insitu Ar⁺ ion sputtering. If the Ar⁺ source conditions are set up in order to perform a “delicate” cleaning on selected small areas, the damage is limited and it might not even be visible to the naked eye. Sputtering may result in surface damage and thus may be adopted only

when there is no other method for analyzing the material.

Physical principles of XPS

XPS is based on the emission of photoelectrons from the atoms of a sample following interaction with soft X-rays having energy higher than the threshold electron energy of the emitting atoms. The photoelectrons are collected by a lens system and they are discriminated on the basis of their kinetic energy by the analyzer.

The experimentally measured kinetic energies (KE) of photoelectrons depend on the energy of the X-ray source ($h\nu$) and the binding energy (BE) of the electron in the atom according to the following equation:

$$KE = h\nu - BE - \Phi_s \quad (1)$$

where Φ_s is the spectrometer work function which is determined during calibration of the spectrometer. The electrons may arise from various core- and valence-band levels, the former being the most exploited in XPS.

Elemental and chemical state analysis

Elemental identification is achieved by comparing the BE values of the signals in the spectrum to those of calculated characteristic core- and valence-band electron levels or to local data-banks. The univocal assignment to a given element is based on the fact that the electrons are characterized by an energy state characteristic for each orbital of a given atom. Thus, the electron 1s of the carbon atom has a binding energy of 285.0 eV, while the electron 1s of the nitrogen has a binding energy of 400 eV, and that of the oxygen of 530.0 eV. It is worth emphasizing that two electrons in the same orbital have opposite spin and the electron energy is quantized.

The signals of the spectrum are labeled using the symbol of the element, followed by the energy level (n) and symbol of the orbital (l), so that

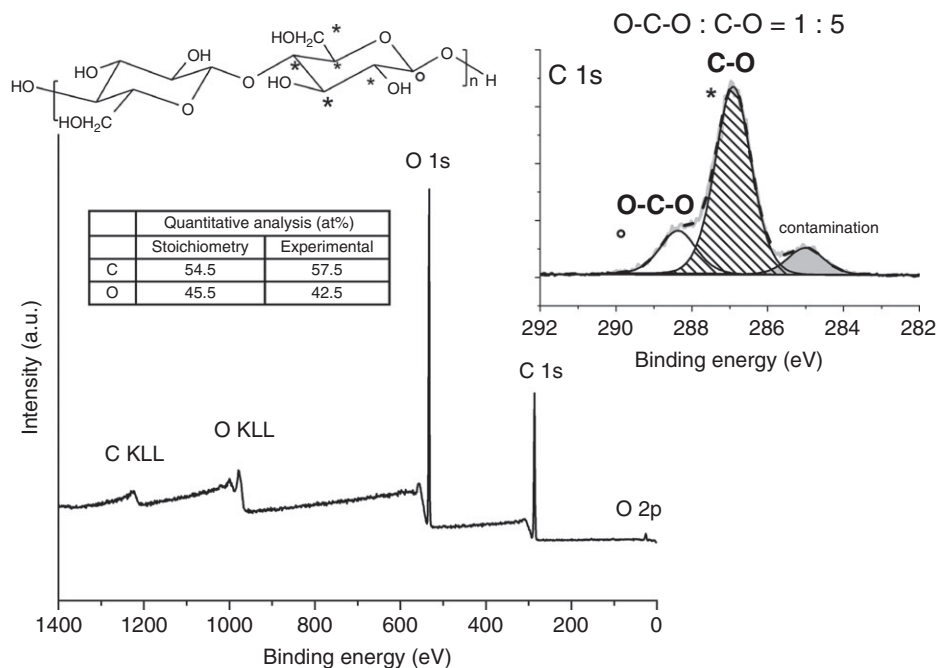


Figure 1 Survey spectrum of pure cellulose.

a signal labeled C 1s (Figure 1) means that an electron was ejected from the level, having $n = 1$, $l = 0$ (orbital s), of a carbon atom.

Elemental analysis is achievable by the so-called survey spectra, in which all the photoelectrons with binding energy values in a range usually between 0 and 1200 eV are displayed. The survey spectrum of pure cellulose is shown in Figure 1: C 1s, O 1s, and O 2p photoelectron peaks are detected together with the Auger signals C KLL and O KLL. The Auger electron signals are due to relaxation of the ions formed following emission of the photoelectrons. In the case of C1s, for example, as a consequence of the photoemission of an electron from the 1s level, a vacancy is formed. Carbon is thus unstable, and to lower its energy two phenomena may occur: (1) an electron from an upper level fills the core vacancy and an X-ray photon is emitted (X-ray fluorescence); (2) an electron from an upper level (e.g., 2p) fills the core vacancy and the energy gain involved in this transition allows the emission of a second electron from the 2p level named Auger electron, which contributes to the XPS spectrum. Following the X-ray notation, the Auger signal is labeled using the symbol of the

element followed by three capital letters (C KLL in the case of carbon Auger peak). The K letter indicates the level 1s, where the primary vacancy is formed as a consequence of photoemission ($K = 1s$); the first L indicates the level from which the electron from the upper level fills the primary vacancy ($L_{2,3} = 2p$) and the second L indicates the level from which the second electron (Auger electron) is emitted ($L_{2,3} = 2p$).

High-resolution spectra focus on a single element and are usually recorded with smaller step sizes and smaller binding energy ranges than surveys (see insert of Figure 1). Furthermore, BE values change when the same element is in different chemical states, that is, in different compounds; for this reason, valuable information on the chemical state of the elements can be obtained by XPS.

The Auger signals may be used also to obtain complementary information on the chemical state of the elements when the chemical shift is not high enough to allow its identification. The combined use of photoelectron and Auger signals in the chemical state plot is extremely useful for identifying the chemical state of the elements.

Quantitative analysis

Since peak intensity is related to the number of photo-emitting atoms, XPS also provides the quantitative composition, in atomic percentages of the elements present at the surface (e.g., table in Figure 1). In the case of homogeneous samples such as cellulose, a simple equation can be used for calculating the sample composition.

Very often, the sample surface of artifacts is not homogeneous in depth due to the presence of a surface film, for example, thin oxide layers, patina on metallic artifacts, or altered outermost layers of polymers or glass. In this case, cleaning by solvents might be applied; alternatively, argon ion sputtering can be performed in situ. More complex mathematical models for quantification might be considered also, and nondestructive in-depth profile as angle-resolved XPS (ARXPS) might be a useful resource in the case of thin layers (<10 nm).

Sputtering depth profile

The surface of the sample is cyclically Ar^+ sputtered. After each sputtering cycle the spectra are acquired and if the sputtering rate is known it is relatively easy to reconstruct the concentration versus depth profile. This technique should be avoided in heritage studies in order to preserve the artifacts. Furthermore, Ar^+ bombardment may induce changes in the subsurface region since only about 1 percent of the impact energy is used for sputtering. An example of the alteration induced by Ar^+ is reported in a study of the corrosion patina formed on bronze surface, where the authors (Squarcialupi et al. 2002) found the presence of copper sulfide in the patina, but they demonstrated that the presence of sulfide was due to the decomposition of CuSO_4 under ion bombardment.

Three-layer model

For samples whose surface comprises a thin oxide layer (surface film) on a metallic substrate, the three-layer model (Figure 2) is suitable to be used (Rossi, Elsener, and Spencer 2004). Each

of the layers, substrate, surface film, and contamination layer, is considered homogeneous in thickness and composition. Photoelectrons from the metallic substrate are attenuated by the oxide and by the contamination layer; photoelectrons from the oxide layer are attenuated only by the contamination layer. Based on a single XPS measurement, the three-layer model allows determining the thickness of both the oxide (t) and the contamination layers (l_c) and the composition of the oxide and of the interface beneath that might differ from the bulk composition (Figure 2). This model has been successfully applied to historical brass wind instruments, to study the thickness and the composition of the oxide layer formed upon contact of brass alloys with saliva.

ARXPS in-depth composition profile

An alternative way to obtain information about the in-depth distribution of elements in nonhomogeneous nanometric-thick layers requires acquisition of the spectra at different emission angles, in a so-called angle-resolved XPS (ARXPS) experiment. Since the sampling depth is related to the emission angle, spectra acquired at different emission angles provide the composition at different depths. To obtain the in-depth composition profile from the composition versus angle experimental results, algorithms have to be applied to the experimental data (Rossi et al. 2004).

Another model that allows reconstructing depth profiles was developed by Tougaard and provides a quantitative estimate of atoms in depth distribution within the outermost surface region, but requires spectra acquisition of highly pure reference compounds to simulate the sample spectrum: With this model, a few model structures can be verified and a maximum of six structural parameters can be determined.

Examples of XPS applications

Pottery

Several studies are reported in the literature on XPS characterization of pottery (see ELEMENTAL ANALYSIS OF POTTERY). These studies involve surface characterization with different

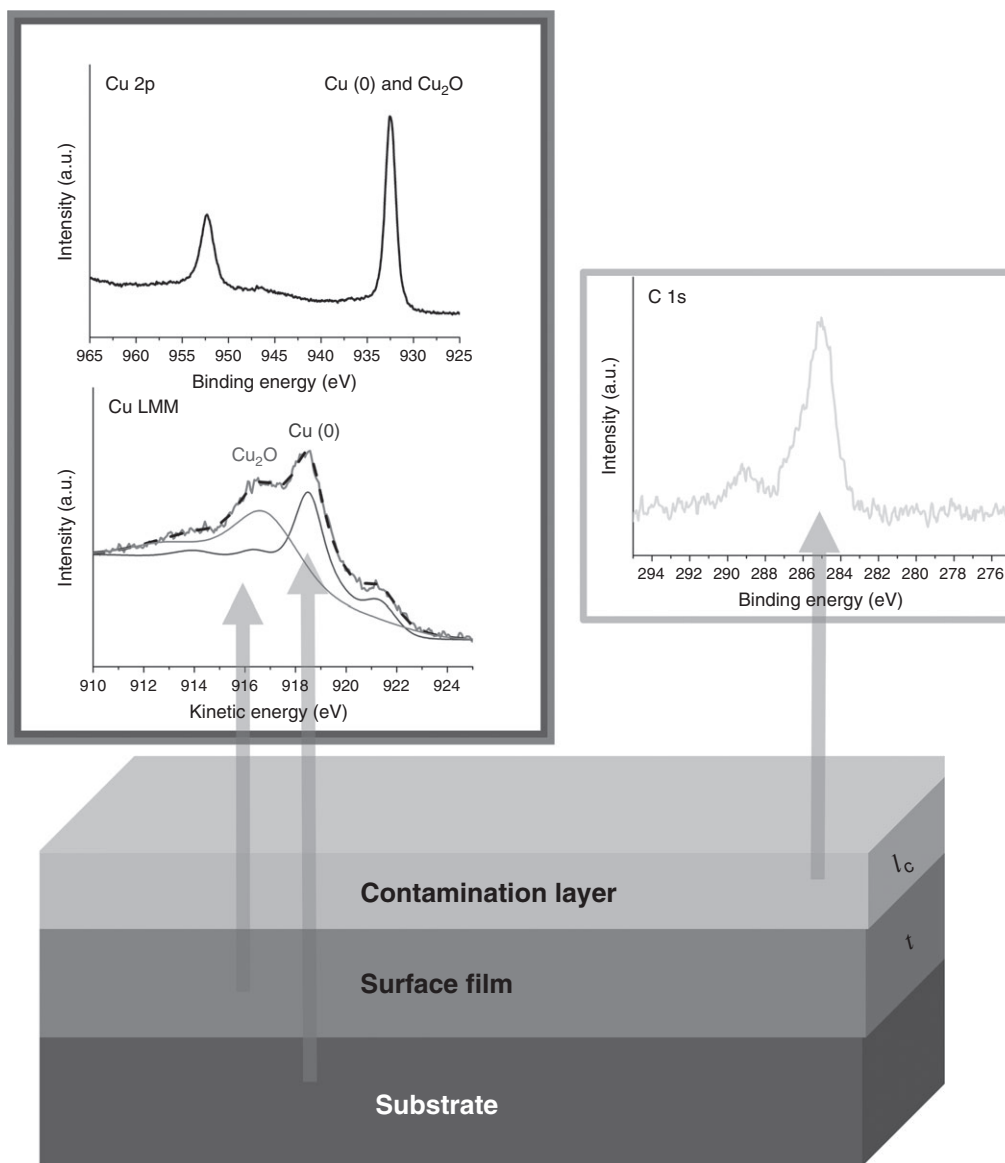


Figure 2 Three-layer model.

purposes: for example, provenance studies, conservation/deterioration studies, investigations on color and chemical state of the elements, and researches aimed at improving the knowledge of the technological skills of potters.

XPS was exploited to gain information about the provenance of pottery by means of the (Al+Fe)/Si ratios obtained by XPS quantitative analysis.

In a multi-technique study by Casaletto and colleagues (2006) the authors characterized the conservation state of medieval pottery from Caltagirone (Sicily, Italy) in order to identify the possible causes of alteration and/or degradation phenomena for both the ceramic body and the polychromatic glaze of the artifacts. Based on XPS analysis, the authors provide evidence of the presence of a carbonate-bearing, protective layer

on the surface of the glazes. The carbonate content decreased in the partially deteriorated samples, exposing lead, which was typically present in Islamic ceramics. A comparison between the surface and the bulk composition (achieved by energy dispersive X-ray (EDS) analysis) allowed the authors to observe devitrification phenomena at the surface and alkali depletion.

The roles of iron and manganese oxides in red, brown, and black decorated shards of pre-Roman pottery from southern Italy (Canosa) were examined by XPS by Sabbatini et al. (2000).

Ancient glass

XPS was used as a complementary technique in multi-analytical study applied to ancient glass characterization. Due to the high surface sensitivity, it allowed the investigation of the surface deterioration of glasses due to weathering. Furthermore, XPS was exploited for determining the chemical composition and identifying the chromophores of colored glasses (see GLASS COLOR), providing the chemical state of the elements and helping in shedding light on the knowledge of ancient glass-makers (Angelini et al. 2004). The effect of cleaning treatments of glass surfaces was also studied by XPS, indicating that the use of chelating agents to remove encrustations from corrosion processes has to be avoided.

Metals and alloys

Most of the work on XPS application to metals and alloys (see CHARACTERIZATION OF METALS AND ALLOYS) of historical interest is devoted to study the composition of the patinas on bronzes and brasses. The sacrificial role of tin in bronze that prevented copper oxidation and the formation of “white lead” $[2\text{PbCO}_3 \cdot \text{Pb}(\text{OH})_2]$ at the surface of Roman leaded brasses of the third century BCE were demonstrated by Paparazzo and Moretto (1995). XPS was also exploited for calibration purposes of miniaturized optical sensors for nondestructive, in-situ analysis of patinated bronze and copper: The XPS experiments, carried out at liquid nitrogen temperature to prevent damage of the patina, allowed distinguishing among brochantite $(\text{Cu}_4(\text{OH})_6\text{SO}_4)$ and

antlerite $(\text{Cu}_3(\text{OH})_4\text{SO}_4)$ which are the principal corrosion products on copper and bronze upon exposure to urban and industrial atmosphere, and chalcantite $(\text{CuSO}_4 \cdot 5\text{H}_2\text{O})$ which is an indicator of the degradation of the protective patina due to acid rain and fog (Schlesinger, Klewe-Nebenius, and Bruns 2000). Similarly, XPS was used for the “calibration” of a miniaturized nondestructive electrochemical sensor used to monitor in situ the corrosion state of historical brass wind instruments: In this context, XPS information on both model alloys having the same composition of brasses used during the nineteenth century and on real specimens was related to the electrochemical response of the electrode, thus giving the possibility of obtaining the chemical composition from open-circuit potential and polarization resistance measurements. Such studies allowed observing the formation of a protective film mainly composed of CuSCN and $\text{Zn}_3(\text{PO}_4)_2$ upon contact between brasses and artificial saliva (Cocco et al. 2016).

Paper and writing supports

Despite the potentialities of XPS in detecting the surface qualitative and quantitative composition of artifacts of historical interest, few studies dealing with XPS applied to ancient papers (see PAPER ANALYSIS) have been published. In Righini et al. (1998), the deterioration of ancient papers produced in Europe between the fifteenth and eighteenth centuries is reported. According to the authors, the use of gelatin in the sizing process and the addition of calcium carbonate during paper production influenced the conservation state. The N/C and Ca/C ratios determined by XPS analyses allowed distinguishing among papers differently conserved, and the results showed that the higher those ratios, the better preserved the papers.

SEE ALSO: Deterioration of Metals

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X-Ray Radiography

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X-ray radiography is an imaging technique widely applied in the field of heritage since the discovery of X-rays by the German physicist W. C. Röntgen in 1895. In fact, even before the establishment of radiology as a medical specialty, radiological examinations were performed for studying mummies and other archaeological finds. In March 1896, Walter Koenig, a lecturer at the Physical Society in Frankfurt, published a monograph reporting on the radiographs of the knees of an Egyptian child mummy and the upper part of a cat mummy. A paper published by Culin two years later describes the work carried out in 1897 by Charles Leonard to produce radiographs of a Mochica mummy and other artifacts from the University of Pennsylvania Museum. Prior to this, in order to gain knowledge or simply to satisfy curiosity, many mummies had been unwrapped, suffering damage and in some cases even total destruction in the process. Koenig also made the first so-called “shadowgraphs” of paintings. X-rays were occasionally used to reveal forgeries or hidden signatures, but generally speaking, before World War I there was no systematic application of X-ray radiography to the study of paintings. A turning point occurred in 1925, when Alan Burroughs embarked on an extensive research project at the Fogg Art Museum in Harvard, with the aim of creating an archive of X-ray shadowgraphs. After purchasing X-ray equipment, Burroughs visited numerous museums in the US and Europe, collecting radiographs of famous paintings of mainly Italian, Dutch, and Flemish Masters. The “expeditions” of Burroughs renewed interest in the use of radiography, leading to the setup of X-ray labs in several American and European museums.

Today, radiography is increasingly being used in the study of archaeological finds and

works of art. It is a non-destructive technique, capable of providing insight into the internal structure of objects, by revealing features and details that would otherwise be invisible. Radiography can help scientists to answer many questions about the constituent materials, manufacturing techniques, and functions of an object; it is a useful and sometimes essential resource for restorers and conservators also, as it can reveal cracks, corrosion, and previous restoration work.

Physical basis of X-ray radiography

X-rays are a form of high-energy electromagnetic radiation, produced when fast-moving electrons interact with matter. X-rays are commonly characterized by their energy (E) or by their wavelength (λ) and frequency (ν). These properties are related by the following expression:

$$E = \frac{hc}{\lambda} = h\nu \quad (1)$$

where h is Planck's constant and c is the speed of light in a vacuum.

The physical principle on which radiography is based is the differential absorption of X-rays (see X-RAY ABSORPTION SPECTROSCOPY (XAS, EXAFS, XANES)) as they pass through matter, as this is responsible for the contrast in images. In a typical setup, the radiation is emitted by a source and detected by an appropriate detector after interaction with the object studied (Figure 1). Various interaction phenomena (photoelectric absorption, Rayleigh and Compton scattering, production of secondary radiation) may occur with different probabilities depending on the energy of the radiation and the nature of the materials making up the object. Consequently, the intensity of an X-ray beam decreases as it travels through matter. The Beer-Lambert law describes the attenuation of a monochromatic X-ray beam produced by a homogeneous material:

$$I(x) = I_0 e^{-\mu x} \quad (2)$$

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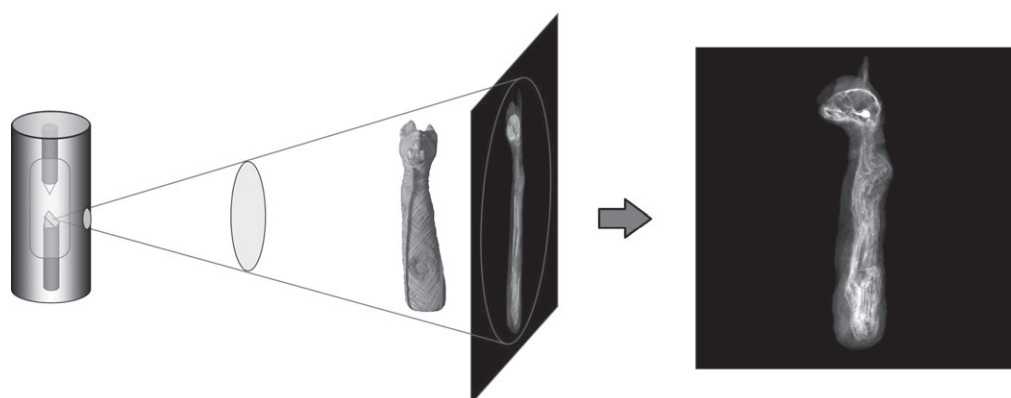


Figure 1 Scheme for a typical radiographic setup, with a radiation source, an object to be analyzed, and a detector for recording the image. Image courtesy of Dr Matteo Bettuzzi, Department of Physics and Astronomy, University of Bologna.

where $I(x)$ is the intensity of the radiation transmitted, I_0 is the intensity of the incident radiation, x is the thickness of the material, and μ is the linear attenuation coefficient (in units of cm^{-1}), which depends on the atomic number and density of the material and on the X-ray energy.

Generally speaking, elements with high density and high atomic number absorb X-rays more than lighter elements. For example, in the radiography of paintings, metal nails or dowels, and pigments such as vermilion and lead white, which contain heavy elements (mercury and lead, respectively), will produce a good radiographic contrast with canvas or wood.

X-ray sources

The X-ray source most frequently used for the radiography of cultural objects is the X-ray tube, which is a high-vacuum tube inside which a heated filament in the cathode produces a steady stream of electrons. The potential applied between the cathode and the anode accelerates the electrons toward the target, where most of their kinetic energy is converted into heat (typically around 99%), and the remaining fraction into X-rays. The spectrum of X-rays obtained is the sum of two components: the characteristic or line spectrum of discrete energies, and the continuous or “white” spectrum, also known as *Bremsstrahlung* (or braking) radiation. The intensity and penetration power of the X-ray beam can

be changed by varying the cathode current (mA) and tube voltage (kV). In particular, increasing the current will increase the number of the X-rays produced, but not their energy, while increasing the potential will increase both the maximum energy and overall intensity of the X-ray beam.

Due to the great variety in size, density, and materials typical of heritage assets, different X-ray sources must be used in order to obtain optimal results (Casali 2006); in particular, a crucial factor is the selection of the energy most appropriate for the thickness and nature of the material. For example, the radiographic examination of paintings and low-density materials, such as paper and textiles, requires the use of soft X-rays with energies lower than 30–40 keV. The great majority of radiographic studies in the heritage field have been conducted using laboratory or transportable setups with X-ray tubes of up to 200 kV; however, in the case of large artifacts and metal or stone objects of considerable thickness, a highly penetrating, high-power radiation source is required. Most frequently, orthovoltage X-ray tubes, developed for nondestructive testing in the industrial field, are used, but radiographs of bronze or marble statues have been obtained using γ -ray sources in the past (mainly ^{60}Co and ^{192}Ir). More powerful setups (betatrons and linear accelerators) exist, but their application in the field of heritage study and diagnostics is still limited.

Detectors for analog and digital radiography

The differential X-ray absorption by the object studied produces some local changes in the intensity of the transmitted radiation which give rise to the so-called “primary radiological image”. Since the human eye is insensitive to X-rays, this image must be converted into a visible one by means of a suitable detector. Photographic films have been used for this purpose for decades, but nowadays they are being increasingly replaced by a variety of detectors for digital radiography, such as photostimulable phosphor plates, fluorescent screens with charge-coupled device cameras, and flat panel detectors. Today, X-ray films still have better spatial resolution (about 10 μm) than phosphor imaging plates and other digital detectors (40–200 μm); their limited dynamic range, however, often requires testing exposures to determine the best combination of acquisition parameters (voltage, current, and exposure time) (Alfeld and Broekaert 2013). Moreover, when a wide range of radiographic densities is present in the investigated artifact, it might be necessary to take images at different X-ray energies. Otherwise, with a digital detector, a single exposure is usually sufficient, thanks to its high dynamic range, as well as the possibility of optimizing the visible gray levels in the image. Other advantages of digital detectors include a lower dose, no need for chemical reagents, real-time response, and image access from remote locations.

Examples of application of X-ray radiography to cultural material

Radiography is a versatile imaging tool: most materials, including ceramics, stone, metal objects, and organic items, such as wood, textiles, and human remains, can be radiographed with satisfactory results. A broad overview of the application of radiography to different kinds of cultural materials can be found in Lang and Middleton (2005).

For example, as previously stated, X-rays have been used since their discovery to investigate ancient mummified bodies for different

purposes: the study of embalming techniques, search for jewelry and amulets in Egyptian mummy wrappings, determination of age and sex, detection of diseases and physical traumas, and identification of fakes and forgeries (Chhem and Brothwell 2008).

The analysis of soil blocks from excavations is another interesting application of radiography in archaeology. In fact, particularly fragile and complex finds or assemblages of objects are not recovered on-site, but are often lifted together with the block of surrounding soil in order to allow safe transport to the laboratory and then subject to careful micro-excavation in a controlled environment. Radiography is invaluable in the clarification and location of the contents of a soil block when laboratory excavation is performed (Shearman and Dove 2005): it helps to preserve even the smallest fragments of the object, as well as delicate materials such as textile remains. For example, Figure 2 shows a picture and two radiographs, viewed from different angles, of a soil block ($40 \times 15 \times 10 \text{ cm}^3$) extracted in the necropolis of Villalfonsina, discovered in the province of Chieti (Abruzzo, Italy) and probably dating back to the sixth to fourth centuries BCE (Re et al. 2015). The radiographs reveal the presence of a fragmented bronze belt that was placed around the body of the deceased.

Archaeological investigations frequently bring to light numerous metal finds. These can be X-rayed as part of the post-excavation procedures to assist in determining the function of the finds and the method of manufacture. In fact, the identification of an object is not always immediately obvious if it is covered with corrosion products, as is frequently the case with excavated ferrous material as a result of their burial. In this case, X-ray radiography can contribute to the characterization, technical description, classification, and dating of metal artifacts (see CHARACTERIZATION OF METALS AND ALLOYS). For example, ancient coins with surface details obscured by accretions can be identified by radiography in some instances. In addition, the radiography of metalwork provides a long-term visual record of unstable and potentially deteriorating artifacts.

Pottery is another material frequently found in archaeological excavations. The radiography

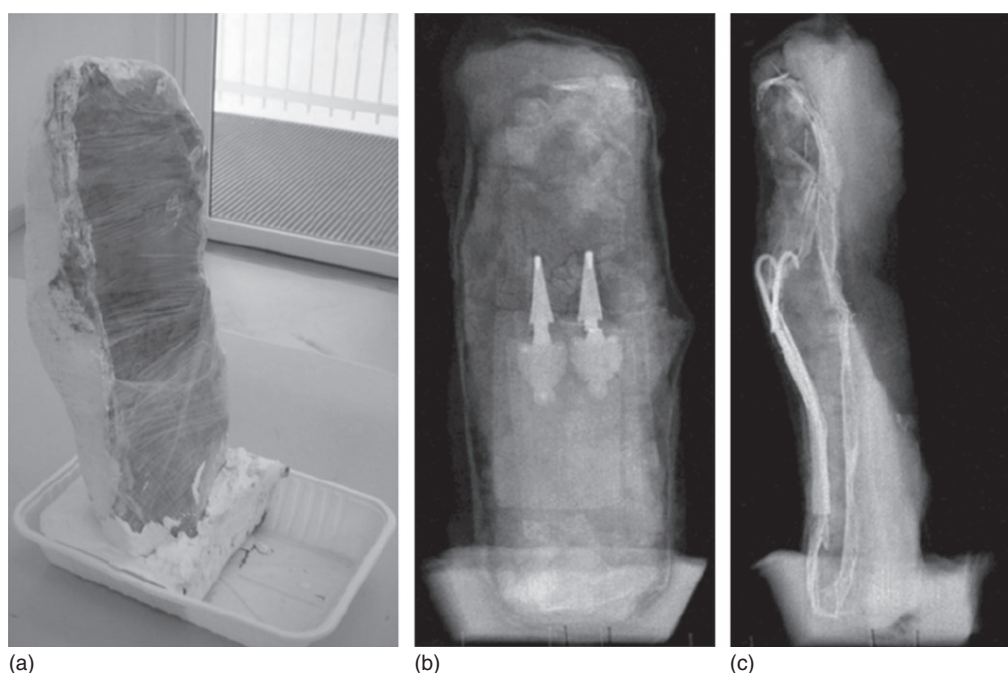


Figure 2 A picture (a) and two radiographs (b–c) viewed from different angles of a soil block extracted from the necropolis of Villalfonsina (Abruzzo, Italy), dating back to the sixth to fourth centuries BCE. The radiographs reveal the presence of a fragmented bronze belt. From Re, A., J. Corsi, M. Demmelbauer, et al. (2015). “X-Ray Tomography of a Soil Block: A Useful Tool for the Restoration of Archaeological Finds.” *Heritage Science* 3: 4–10; Springer Open Access article distributed under the terms of the Creative Commons Attribution License: <http://creativecommons.org/licenses/by/4.0>.

of ceramics (see X-RADIOGRAPHY AND CERAMICS) may be useful mainly for two purposes: characterization of the clay fabrics, and investigation of shaping and fabrication techniques (Carr 1990; Berg 2008). Unlike modern ceramics, archaeological pottery was commonly made from clay pastes containing coarse, aplastic inclusions that may have been either intrinsic to the clay or added, as tempers, by the manufacturer for various reasons. Even though the contrast is generally limited, radiography is able to visualize the size and shape of aplastic inclusions, as well as the voids left by organic matters (e.g., chopped grass or chaff) burned out during the firing of the pottery. This information can be useful for characterizing clay pastes derived from particular sources or prepared in special ways. Radiography can also be helpful for other aspects of the study of ceramics: for example, it may reveal old breaks and repairs, show the contents of still-sealed vessels, and unmask fakes.

Lastly, another common application is the X-ray examination of paintings, which is able to provide us with information on many aspects, such as:

- the state of conservation of both the paint layer and the support;
- the possible existence of changes in the paint layer (the so-called “pentimenti”) and/or underlying paintings;
- the presence of previous restoration work;
- the painting technique of a certain artist;
- the authenticity of a work of art.

In examining items of archaeological interest, X-ray and neutron-based imaging techniques (see NEUTRON RADIOGRAPHY AND TOMOGRAPHY) may provide interesting complementary information, especially when the examined object has a composite structure made of metal and organic materials. In fact, unlike for X-rays,

neutrons are attenuated by some light elements (e.g., H, Li, B), for which X-rays do not provide a good contrast, whereas they easily penetrate thick layers of metals like Pb, Fe, and Cu, where standard X-ray imaging would fail.

Sometimes radiographic images are difficult to interpret because of an important limit of radiography: the superimposition of features belonging to different layers of the object. In fact, in conventional radiography, a three-dimensional subject is projected onto a two-dimensional detector; therefore, information with respect to the third dimension (depth) is lost and each point of the resulting image provides a measure of the overall attenuation of the X-ray beam as it passes through the object. This limitation has normally been overcome by taking radiographs from different angles or by using X-ray stereoradiography, a technique based on the acquisition of two radiographs from slightly different viewpoints; their viewing through an appropriate apparatus gives a 3D image. In addition to the application in medicine, stereoradiography has also been applied to cultural materials, being particularly useful for ceramics, human remains, and wooden statues (Lang and Middleton 2005). Stereoradiography, however, has become essentially obsolete after the introduction of computed tomography (CT) in the early 1970s. This technique is able to provide a 3D reconstruction of the inner structure of the objects studied, while preserving their integrity. Even though CT is primarily used as a diagnostic tool in the medical field, in recent years its importance and potential when applied to cultural materials has become increasingly apparent. After its first use for the examination of mummified human and animal remains (see, for example, Hoffman, Torres, and Randy 2002), a growing number of authors have reported the successful use of CT in the study of archaeological finds and works of art; it can be therefore expected that the application of this technique will increase further in the future.

SEE ALSO: Computed Tomography;
Deterioration of Metals; X-Ray Radiography and
Material Analysis; X-Ray Tomography

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X-Ray Tomography

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In order to study, restore, and better preserve archaeological finds, several non-invasive diagnostic techniques are being used with increasing frequency. Among these, CAT scanning (computer-aided tomography, also called CT: computed tomography), routinely used in medical diagnosis, is playing an important role in obtaining detailed views of objects of antiquity (see COMPUTED TOMOGRAPHY). The result of a CT scan is a 3D volumetric image that contains information on the structure and composition of objects and assemblies. The input data for the 3D inspection image is a set of radiographic transmission images acquired at different angles with respect to the source–detector beamline. Usually the object is rotated 360° with small angular steps. If 0.5° rotation steps are used, 720 digital images are obtained. If the object cannot be moved, the acquisition system (radiation source and detector) rotates around it. These images, processed with suitable mathematical algorithms, make it possible to reconstruct the different internal structures of the object/assembly.

The object is “virtually” rebuilt by bringing together the various sections into a single volume. Further processing, such as “virtual volume cuts,” can reveal many internal details. The CT image is composed of many small volume elements—called *voxels*—as with LEGO™ construction toys. The smaller and more numerous the voxels are, the higher the image definition. Spatial resolution for CT inspection images can be quite small, but this impacts both the field of view for the scanning and certain requirements for the data acquisition. The result is that for high-fidelity 3D CT inspections, several thousand radiographs may be acquired (Brancaccio et al. 2011).

Instrumentation

The equipment for CT acquisitions consists of five components: (a) the radiation source to be used (X-rays, gamma rays, or neutrons); (b) an acquisition system for the digital radiographic transmission images produced by the interaction between the object and the source (i.e., scintillators coupled to amorphous silicon arrays, CMOS arrays, cameras or linear diode arrays); (c) a rotating platform upon which the object to be inspected is situated, or a mechanical system (source plus detector) that rotates around the object, as in a medical CT; (d) a computer to manage the image acquisition (object handling, operation of the source and the system); and (e) a computing system able to provide the image “virtually” reconstructed, even at a later time.

Acquiring high-quality CT inspection data requires the choice of several key parameters for scanning, and each choice can involve “trade-offs”. The type of penetrating radiation and the energy selected is fundamental: if the radiation is too weak (from the energy standpoint), it does not pass through the object; if it is too strong it is not attenuated enough and therefore does not yield information. A physical analysis of the thickness and composition of materials can point to an “optimum” radiation energy (sometimes a couple of choices emerge for gamma-rays, X-rays or neutrons). CT inspections at low to medium energies can be non-invasive, but some effects on the object occur for higher energies (for instance, color changes in the material, or activation from high-dose rates).

For the analysis of objects in the archaeological field, we can subdivide the tomographic systems with photon sources into three classes: (1) high spatial resolution systems (micro- and nano-CT) with low voltage sources, which are mainly used for small items; (2) systems for objects of mean size and not-too-high density, with X-ray sources with a 200–600 kV voltage; (3) systems with

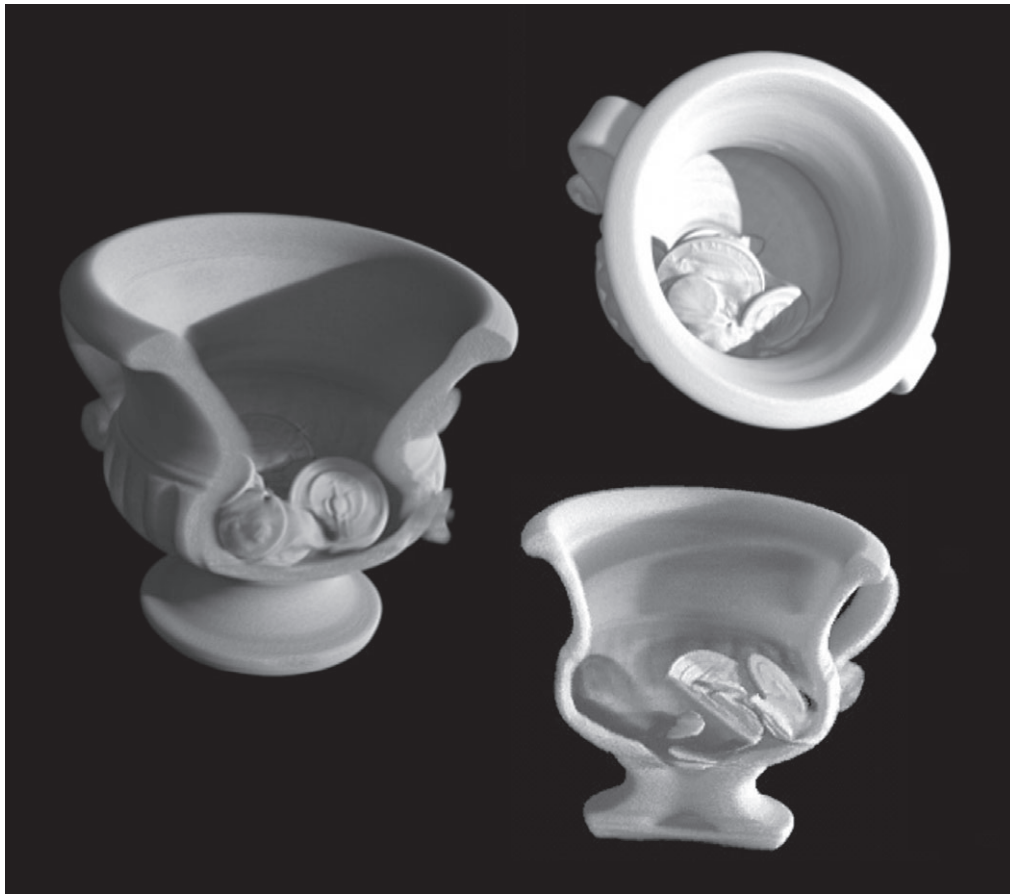


Figure 1 A mock-up of an ancient treasure (a clay cup with some bronze coins) inspected by X-ray CT. Reproduced with permission from: Berdondini, A., R. Brancaccio, V. D’Errico, A. Miceli, M. Bettuzzi, F. Casali, M. P. Morigi, M. Senn, and A. Flisch (2011) “The Use of Industrial Computed Tomography in the Study of Archaeological Finds.” *Proceedings of the 37th International Symposium on Archaeometry*, edited by I. Turbanti-Memmi, 575–78; Springer-Verlag.

high voltage sources (greater than 1000 kV), called LINACs (linear accelerators), which are able to scan large-size and high-density finds; (4) radioisotopic sources that emit photons with energy greater than 1 MeV.

Up until a few years ago, high-energy sources were radioisotopic sources (mainly Co-60 and Ir-192). These sources are still used for some industrial applications. Their advantages include low cost and portability, but the disadvantages include “larger focal spots” (problematic for obtaining better spatial resolution), and comparatively low intensity. In addition, the transportation of radioactive sources outside of shielded and controlled environments is much

more dangerous. Machine sources (X-ray tubes and LINACs) are higher output, include smaller focal spots, and can be fully interlocked for safe operation.

LINACs are commonly used in industrial inspections as a source of high-energy X-rays (2–15 MeV). In this modality, accelerated electrons impinge on metal plates (usually copper or tungsten), thus giving rise to the “radiation of *Bremsstrahlung*” (X-rays). Recently, some small electron accelerators, called *betatrons*, have been used in field-portable systems for inspecting infrastructure objects (Martz et al. 2016) using MeV energies (up to 8 MeV). While both LINACs and betatrons have been used

in “object-stationary” systems, betatrons are smaller and more portable. (For an example of a portable betatron, see <http://www.globalxray.com/industrial-radiography/>) In the future, these machines will be of great interest for inspecting objects that cannot be transported to the laboratory (statues, columns, excavation blocks, and so on).

High spatial resolution tomographies can be obtained by micro-CT systems. In this case, the source of X-rays, a micro-focus tube, can include focal spots of 5–100 microns and a 1–500 μA current. The spatial resolution is in the 10–20 micron range. To obtain higher spatial resolutions, one can use a *nano-focus* source where the focal spot is around several hundred nanometers. Accordingly, the output current of this source is very weak (usually less than 100 μA) and the system can only be used to analyze either very small objects or low-attenuation materials.

While most machine X-ray sources are poly-energetic, single-energy sources are available. A single-energy source can acquire the most quantitative radiographic data that does not include some of the artifacts common to poly-energetic source (i.e., beam hardening). CT scans can be acquired at the “optimum” energy, or perhaps at a number of single energies, and the scans taken together can be used to perform detailed materials characterization (Martz et al. 2016). Third-generation “synchrotrons” include the ability to scan a single-energy over a significant range (up to 100 keV) (see SYNCHROTRON-BASED X-RAY ANALYTICAL TECHNIQUES AND MATERIALS ANALYSIS). Synchrotrons also provide an opportunity for “phase-contrast” inspections, a powerful high spatial resolution modality for low energy (Gerlach et al. 2006).

Micro- and phase-contrast CT in archaeology

Micro-CT applications in archaeology extend to parts of ancient human bodies, mainly bones and teeth (see BONES AND IVORY) that can be studied “non-destructively”. By using a micro-CT, it was possible to show that, out of 11 human teeth discovered in a Neolithic graveyard in Pakistan, dating back 7,500–9,000 years, nine showed they had received dental treatment in vivo (Coppa

et al. 2006). Further, the analysis of bones, small metal objects, jewelry, and ceramics can be conducted successfully with a micro-CT (Sanger et al. 2013), also uncovering details about life in the ancient past.

Over the past 15 years, the progress made in phase-contrast imaging has made it possible to study compounds of similar objects and low-density materials. A striking example is provided by the study of some carbonized papyri from Herculaneum (Italy), in the so-called “Villa dei Papiri” which, in 79 CE, caught fire due to the eruption of Vesuvius. Six of these papyri belong to the collection of the Institut de France. Two of these (one unrolled and one still rolled) were recently analyzed at the European Synchrotron Radiation Facility (ESRF) in Grenoble, France, in the “biomedical beamline ID17” line. The phase contrast between the ink (coal-based and with a thickness of about 100 microns) and papyrus fibers was sufficient to “read” some sentences written inside the roll (Mocella et al. 2015).

Medium- and high-energy X-ray CT

Average-energy systems (100–450 kV) are those most used in diagnostics for archaeometry because they are easily transportable and fairly low cost.

Within the framework of the European Project DETECT at EMPA—the Swiss Federal Laboratories for Materials Science and Technology (Dübendorf)—CT equipment has been developed, mainly for industrial applications. It has a 450 kV X-ray source and a digital camera detector coupled with a 45×32 cm CsI screen. In order also to assess its application in the field of archaeology, a mock-up of an ancient treasure (a clay cup with some bronze coins) was inspected with X-ray CT (see Figure 1). The resolution is sufficient to read the inscriptions on the coins (Berdondini et al. 2011). In the case of a cup full of ancient coins, the voltage of 450 kV is no longer sufficient and higher-energy sources must be used.

A recent and informative CT scan of a pot full of Roman coins (Miles et al. 2016) was performed by a collaboration between archaeologists and scientists at the British Museum in London, and the University of Southampton, UK, using

MeV energies (see <https://www.theguardian.com/science/2012/jul/09/x-rays-reveal-secrets-roman-coins>).

Ancient bronze artifacts (cups, statues, and so on) are very thin (a few millimeters of metal), as can be seen from a 3D CT of an old Roman bronze statue of Eros (Figure 2) (Bettuzzi et al. 2015). This CT scan was performed at the Getty Conservation Institute (USA) using equipment similar to that developed at EMPA. Unlike ancient bronzes, Renaissance materials can be about one or two centimeters thick. From the CT inspection data, it is possible to identify the casting period of a bronze statue and the technique of casting.

All of these inspections were performed with sources that are not easily transportable and must be used either in bunkers or in specially equipped mobile containers. At the same time, important archaeological discoveries are often

made in inaccessible areas, especially in Africa. In such areas, there are usually no facilities equipped with tomographic systems capable of scanning objects at the target spatial resolution. In these cases, lacking a good CT system in the immediate vicinity, it is necessary to move modern CT equipment to the site. An example of this approach is the CT image of the skull of “Lady Buya”, a prehistoric hominid who lived about one million years ago, found in Danakil (Eritrea) by a joint delegation from the University of Rome and the Pigorini Museum of Rome (Italy). This skull, which is still preserved at the Museum of Asmara, was first scanned with old CT equipment at the local hospital. Since this type of analysis was very important for paleoanthropology reasons (brain volume, etc.), the Department of Physics of Bologna was asked to bring an appropriate tomographic system to Asmara. Even though the local



Figure 2 X-ray CT image of a Roman bronze statue of Eros performed at the Getty Conservation Institute (Los Angeles, USA). From the images it is possible to see how thin the bronze is. Reproduced with permission from: Bettuzzi, M., F. Casali, R. Brancaccio, M. P. Morigi, D. Carson, G. Chiari, and J. Maish (2015) “Computed Tomography of a Medium Size Roman Bronze Statue of Cupid.” *Applied Physics A* 118 (4): 1161–69; Springer.

environmental conditions were not the best, the high-quality system components (200 kV micro-focus X-ray tube and a 40 × 50 cm scintillating screen) meant that results exceeded expectations.

Blocks of soil

Many museum warehouses all over the world hold blocks of soil extracted during excavation campaigns that may contain metal objects of archaeological interest. The extraction of possible finds is expensive and time-consuming (weeks or months). This investment is justified only if the block of soil contains something interesting from an archaeological standpoint. However, sifting the soil in an intrusive way can destroy key evidence in the soil (packing patterns, and evidence of water paths). The type of block determines the characteristics of the X-ray source. The bigger the block dimensions, the higher the required energy of the photons for a robust detected signal. This is an opportunity for 3D CT, a high-quality 3D image of an object contained in any block of soil, which can be then reproduced using modern 3D printing techniques and an appropriate metal material. There are several papers on the CT of “blocks of soil”. At EMPA, researchers studied an excavation block (ca. 100 BCE) with Celtic material inside. The source was a transportable LINAC, with energy of 4 and 6 MeV, capable of operating for several days without interruption—properties that make it particularly suitable for that kind of work (Flisch et al. 2014).

Neutron tomography

In some circumstances, neutrons provide a better alternative for the inspection of hydrogen-rich materials in large structures. While photons mostly interact with the electronic structure of matter, neutrons—particles with no electrical charge—interact with the nuclear structure. The most important interactions of neutrons are “scattering” (interaction with elastic and inelastic collisions), absorption (with subsequent emission of other particles and/or photons), and the fission of particularly heavy nuclei (uranium, plutonium, etc.). Lightweight elements (such as hydrogen,

deuterium, carbon, and oxygen) remove neutrons from the beam through the scattering process.

Other elements (such as boron, copper, and cadmium) remove neutrons from the beam through the nuclear absorption process. Consider a recent study (Mannes et al. 2015) where the same object was inspected with X-rays and neutrons (see NEUTRON RADIOGRAPHY AND TOMOGRAPHY). The radiographic images obtained with the two radiations were very different from each other. A lead object is almost transparent to neutron radiation and opaque to X-rays; the opposite is true for organic materials (cloth, wood, biological tissue, etc.), which are opaque to neutron radiation and almost transparent to X-rays. The two sets of information are complementary, especially when the object under examination is made of both organic material and metal (see NEUTRON IMAGING AND TOMOGRAPHY IN CONSERVATION AND NEUTRON RADIOGRAPHY AND TOMOGRAPHY).

Scanning with both types of radiation is a powerful inspection tool. There are very few research centers in the world that are able to perform both tests of an object in sequence. One of these is the Helmholtz-Zentrum Berlin für Materialien und Energie in Berlin, Germany. Interesting measurements of different objects have been performed with the two radiation sources. The neutrons for experiments were produced in the CONRAD line, which is connected to the BER-II research reactor. As an X-ray source, a micro-focus tube was used.

Another important laboratory for this kind of measurement is the Paul Scherrer Institute in Switzerland (PSI: <https://www.psi.ch/>). Neutron tomography can also be performed by mobile neutron sources, but with poorer results due to the weak neutron output. One side-effect for neutrons is that acquiring high-quality CT requires long scan times; the result is that any object with some metal inside can remain radioactive for varying lengths of time, depending on the nuclear properties of the irradiated material. As a general rule, bronze objects must be kept away from the public for a few days.

CT for education

For archaeology, “dissemination science” specifically devoted to attracting the interest of young

people is very important. CT, which provides information on what we can find inside an object, is a great tool for this kind of knowledge. For students on a museum visit, it is one thing to have simply an uncritical view of a series of dusty Egyptian small mummies, but another to be able to see, through appropriate filmed simulations, what types of animals are contained in them and what their history was. In order to attract the attention of young visitors, at the Civic Museum of Bologna (in the Egyptian section), a screen has been placed near some mummies of small animals (cats and falcons) to show moving images of them, acquired using tomographic techniques.

The precise manipulation of three-dimensional images can inspire students towards the development of new 3D image processing systems. At a Swedish hospital, Egyptian mummies were scanned using a standard medical CT system. The processing of the data, done in an excellent manner, manages to show the various case layers, thus providing a three-dimensional representation of great interest (see <https://www.youtube.com/watch?v=WSJ1hWISITE>).

In conclusion, with the development of instrumentation, methods of numerical image analysis, improvements in X-ray sources and detectors, and advances in computing techniques for 3D imaging, three-dimensional CT is proving to be a very effective technique for the study of objects of archaeological interest, and also for their restoration and conservation. Recently, with new multi-core computers, the processing of three-dimensional images has become faster, thus arousing great interest, especially among young people, who are accustomed to using apps and tablets. In conclusion, even in archaeology—as in many other fields of scientific interest—excellent results can be obtained only through cooperation between archaeologists, restorers, physicists, and experts in digital image processing.

SEE ALSO: Computed Tomography;
Computer-Assisted Restoration; X-Ray
Radiography

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Archaeology and Tourism

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Archaeology has had a contradictory relationship with tourism. On the one hand, the need to disseminate findings and obtain resources has opened up archaeology to the great world of visitors, fans, and tourists eager to increase their cultural capital. On the other hand, there is a well-founded fear of the trivialization and commercialization of vestiges and archaeological zones, due to the arrival of tourists

Archaeological tourism is part of cultural tourism (Herbert 1995). Tresserras (2004, 2) defines archaeological tourism, or archaeo-tourism, as that type of tourism in which archaeological resources become attractions for tourists and/or when the main motivation of the trip is the visit to the archaeological zones, often encouraged by the diffusion of magazines like *National Geographic* and other publications.

Growth of archaeological tourism

Tourism has been a growing industry, especially since the 1980s. According to the *UNWTO World Tourism Barometer*, in 2016, around 1.2 billion international tourists traveled around the world. This makes tourism an important source of foreign currency and an activity that generates jobs whose income impacts the Gross Domestic Product of many countries. As part of this increase, archaeological tourism has also grown. The increase of visitors to archaeological sites in recent decades has been favored also by the declarations on the cultural heritage of humanity on the part of UNESCO (Moreno and Sariego López 2017).

To mention just a few examples, in 2016, 13 million tourists arrived in Cancun, Mexico, of which 2.1 million visited the archaeological zone of Chichén Itzá; 1.7 million visited Tulum;

and Palenque received 655,417 visits. The case of Peru is also eloquent. The number of tourists visiting Machu Picchu grew strongly in the past quarter century, from only 77,295 visitors in 1991 to 1,282,515 tourists in 2015 (Alonso Schwarz 2012). In 2016, almost 1.3 million tourists arrived at this international archaeological zone.

Another illustrative example is that of Angkor, Cambodia. Since the declaration of the archaeological site of Angkor as a World Heritage Site in 1992, shortly after the Paris Peace Accords ended two decades of warfare, tourism development has allowed Cambodia to strengthen its economy. That country received in 1993 a little more than 100,000 tourists; in 2008 it received more than 2 million (Moreno Melgarejo 2013, 112). A similar case is that of Guatemala, whose tourism has become one of the main sources of income after the civil war ended in 1996, where its archaeological sites are one of the main tourist attractions, along with its enormous ethnic and cultural diversity (Sánchez-Espinosa 2017).

In mature tourist destinations, such as the United Kingdom, Spain, and Greece, the number and scale of visits to archaeological sites by tourists has been increasing. For example, in Spain, research projects and the enhancement of archaeological heritage have allowed access to a large part of the country's archaeological resources, with a projection towards the international market. Investments have been made in new museum equipment, the renovation of museums, and the musealization of large archaeological sites.

Archaeological tourism has influenced the creation of products of all kinds to bring archaeology to visitors. The thematic routes stand out, such as Íberos Route 16, the Celtiberia Route, and the Roman Bética Route. There are also shows and celebrations of historical recreation. Tourists are invited to take gastronomic tours of ancient times, or to stay in hotels that preserve Roman archaeological remains in their interior (Tresserras 2004, 3). In the same way, in Mexico, light-shows in the archaeological sites of

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Teotihuacan and Chichén Itzá have allowed the international promotion of tourism (Villalobos-Acosta 2013).

Archaeology in tourism is so important that it is already a market segment. Tresserras (2004, 2) points out that archaeological tourism or archaeo-tourism consists of activities in which archaeological resources become attractions for tourists and/or when the main motivation of the trip is the visit to the archaeological zones.

Relationship of archaeology and tourism

Archaeology and tourism have had a contradictory relationship. While the visit of tourists to archaeological sites and museums has increased throughout the world, the archaeological community does not have a coordinated position regarding this phenomenon. Pinter (2005, 11) points out that there is no consensus on the role tourism has with archaeology. For some archaeologists, tourist activity is a way to attract resources for research and site protection. For others, tourist activity is eminently destructive, as the interests of the market compete with scientific interests. For their part, some sectors in the tourism industry consider archaeologists and their institutions as an obstacle to the development of tourist destinations (Walker and Carr 2013, 20).

Despite the importance of archaeology to tourism, it is difficult to find tourists who travel only for archaeological reasons. Visits to archaeological sites and museums are usually integrated into the trip as an important component in many tourist destinations, but they are not the only reason for traveling. Other frequent components in tourist trips include gastronomy, landscape, the attractions of contemporary culture, and a more generalized historical interest.

The relationship between tourism and archaeology becomes even more complex due to the emergence of a new subject: the indigenous movements. Since the 1970s, native peoples have claimed their right to the human remains located in their territories, as well as to the archaeological sites and material objects built or manufactured by their ancestors. In the United States, Canada,

New Zealand, and Australia, indigenous movements have promoted changes in the legislation on human remains located in the ancestral lands (Díaz-Andreu 2014). They have also had an impact on the content and organization of museums. It is estimated that in the United States, the 1990 Native American Graves Protection and Repatriation Act has caused one-and-a-half million objects to return to native communities. In Latin America, indigenous organizations such as the Maya in Mexico and Guatemala, and the Mapuches in Chile and Argentina claim their participation in the administration and management of archaeological sites and museums.

SEE ALSO: Heritage and Ecomuseums; Heritage and Economics; Planning and Tourism; Repatriation; World Heritage Sites Designation

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Assessment: Heritage Impact (HIA)

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Origins of Heritage Impact Assessment

Impact assessment evolved during the 1960s in response to growing public interest in the protection of the environment from the consequences of development, using models and approaches from the natural sciences, particularly ecology. The aim was to empower the environment in decision-making and development planning. The success of the impact assessment model as a planning tool since the beginning of the sustainable development debate of the 1970s led to its wider application, including applications to heritage. It was first applied to archaeological resources of known importance that were threatened with destruction due to infrastructure development projects. Impact assessment applied to archaeological and other heritage resources is now gaining universal acceptance as an essential development planning and heritage management tool.

Heritage Impact Assessment (HIA) fits into a comprehensive assessment process that links several levels of engagement: Strategic Impact Assessment (SIA) which deals with the potential impacts that will result from area-wide plans or major policy decisions; Environmental Impact Assessment (EIA) which deals with the ascertained impacts that will result from a specific development project, and HIA which is applied to specific project and development proposals that potentially threaten resources of cultural significance.

HIA is a systematic process of identifying the probable results of a proposed policy or action on the heritage of a place and its communities. It is a decision support tool which provides input at the planning, works and operational stages to minimize or eliminate adverse effects through mitigation and to enhance positive impacts. In

places where heritage is included in the EIA system as a component on a legal par with other environmental variables, practice has clearly shown the power of rigorous HIA as a tool to manage change and mitigate risk in order to preserve significance—the basic task of heritage management. As such, it is rapidly becoming the heritage manager's most important tool for managing change in historic resources.

Why is HIA needed?

The aims of HIA are to identify heritage resources, assess potential impacts and mitigate them with a view to preserving and safeguarding heritage resources. HIA is not a proposal for optional scenarios or a statement of heritage's self-evident importance. What it must be is a measured, thorough presentation of facts and arguments and a realistic set of proposals for remedial and ameliorative action. It is the professional task of the HIA practitioner to find an acceptable approach which will preserve heritage values, satisfy as many stakeholders as possible, and be financially viable and practicable in conservation terms.

The assessment of impacts on heritage is needed today as cultural resources are being not only lost to development, but also exploited at an unsustainable rate. Heritage managers are faced with two principal challenges: ensuring the continuity and continued relevance of culture in the community and protecting both the fabric and significance of heritage assets from exploitation, misuse and degradation as a result of change.

HIA provides the methodology to safeguard the integrity of heritage resources in the face of these threats from development, or other scenarios of external change; to negotiate a sustainable balance between the forces of change, progress, and conservation in ways that maintain the authenticity of the threatened heritage, preserving its significance, meaning, and function in the life of the community; and to mitigate the adverse impacts of development and change, enhancing and adding value to the heritage as a result.

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What type of heritage is assessed?

There are different definitions of what type of heritage should be assessed in an HIA. Tangible, immovable heritage is accepted as the main focus with an emphasis on listed, nationally, and internationally protected heritage. Intangible heritage, however, is not considered in the HIA processes of international funding agencies and many national frameworks. When referred to it is often restricted to discussion of ways that intangible resources can be “used” for commercial purposes or in the restricted context of safeguarding the cultural heritage of indigenous peoples (IFC 2012).

The setting of heritage resources is another critical component of their significance and authenticity which is often neglected by the HIA process, despite such recommendations as the Xi'an Declaration (ICOMOS 2005) article 8.

Some systems recommend that given constraints of time and money, assessment should focus on the most significant impacts in order of priority; the problem with this approach is one of sequence where someone has to identify what are the “most significant impacts” before the impact assessment itself is carried out (Campbell 2009). This concept of “critical cultural heritage” is dangerous as it implies that only high-profile, legally protected and well-defined “used” resources need focused protection.

One of the thorniest issues in HIA is that of “potential” heritage. Resources which have legal protection or international recognition are guaranteed to receive attention, with other resources positioned along a diminishing scale of likelihood. At the bottom lie the vast undocumented areas of archaeological and heritage potential. Most frameworks provide no guidance on how to tackle predictive modeling, sampling, or investigative survey and instead rely at best on “chance finds” procedures, emergency excavation, or relocation, and at worst lead to loss of valuable places. This is a matter of particular urgency for countries with large tracts of unstudied and undocumented potential.

HIA methodology

The shared approach to design and implementation of HIA is based primarily on that of EIA as a whole, and within this framework a standardized methodology is being developed (Asian Academy for Heritage Management online). An HIA is carried out when it is red flagged during the development process as a result of “screening,” a review of all project proposals to identify those which may have potential impacts on heritage. The nature and scale of the HIA baseline study, including definition of the study area, requirements for the desk-based study, field surveys and any additional data collection and the staffing and expertise needed for the HIA team are identified as part of “scoping” and writing of the terms of reference.

The methodology used in HIA is based on a comprehensive understanding of the current or baseline situation; the type, distribution, and significance of heritage resources as revealed through desk-based study and additional data acquisition, such as archaeological investigations, built heritage surveys, local interviews, and recording of crafts, skills, and intangible heritage. This is systematically integrated by the use of matrices with information on the nature and extent of the proposed engineering and other works to identify potential sources of impacts on heritage. Mapping of location and distribution of heritage in relation to proposed works or changes is a critical component of this baseline along with the assessment of the condition of resources.

The “significance” of heritage resources is a fundamental part of the process and should be assessed and factored into the overall assessment of impacts being weighed carefully against predicted impacts and the proposed public benefit that will result from loss or compromise to the heritage. This is where training, experience, and professional qualification come into play.

Assessment is then made of each specific impact during the proposed works, for the lifetime of the development and during decommissioning, and an overall assessment of the degree of resulting change. It is very noticeable that guidance documents regularly gloss over the section on implementation of the assessment of impacts. There may be a few hints, examples

of simple matrices or an abstract flow chart but nothing to reliably guide the practitioner through the very complex and demanding tasks of identifying the potential sources of impacts, their nature and extent, how they will combine to act on existing conditions and how they will affect the significance of parts of heritage and the whole.

Several cultural heritage impact assessment (CHIA) methodologies base their assessment on project types such as pipeline, roadworks, mining, port development, or sewerage and provide sectoral guidelines. These describe the types of works associated with the project type and generalized impacts that will result. These can be useful to some extent, but a detailed understanding of engineering works is fundamental, as the distinction between different piling methods, backhoe blades and dredging methods is critical to assessing their impacts.

Detailed proposals are put forward to mitigate the identified negative impacts where necessary with the aim of either maintaining the current status or improving it. Essential tools are designed to monitor the success of the proposed mitigation. Mitigation is essentially a set of proposals to try and maintain the condition of heritage resources at the level described in the baseline study or to improve them. Mitigation proposals must include a monitoring plan with indicators to illustrate the degree of change from existing conditions to during and postproject conditions to evaluate how affectively this is achieved and to ensure that the required mitigation measures really are implemented as laid out in the HIA.

The strength of this process comes from the integration of spatial and distributional data, predictive methods, rigorous matrix methodology, and the consideration of multiple scenarios and solutions based on an understanding of the significance of heritage resources in relation to issues of “public good.”

Who does what and why it matters

Because HIA is integrated into larger strategic plans and development projects, there are players at a number of different levels. There are those who decide whether or not a proposed project needs a HIA, those who write the scope and

tender documents, specialists who actually implement the HIA, reviewers who assess the HIA and approve the project, and finally, those who implement and then monitor mitigation measures.

It is widely acknowledged that professional input into this complex process is essential, but approaches differ on the degree of such input and at what stage it should be required. Some apply strict vetting and listing of professional qualifications while others work on the underlying assumption that a HIA will not be carried out by heritage professionals at all. It is accepted that in the majority of cases it be carried out by someone who is appointed to be the heritage generalist. They will come from some other background, and will most likely be covering heritage on a part-time basis while still being responsible for their own discipline. Heritage practitioners are consulted but not integrated into heritage identification and safeguarding except in “exceptional cases” (Campbell 2009). As a result, there is a risk that poorly informed decisions at the early stages of the HIA will negate later findings and compromise the effectiveness of the whole process.

At stake are issues of transparency and integrity. Professional input is required at every stage of the HIA process, including the early stages of screening to avoid over-reliance on existing heritage lists and inventories and scoping when knowledge of local heritage, project cycle and engineering works is critical. Baseline studies, including additional surveys and studies, as well as the assessment and mitigation design should be carried out by qualified and experienced HIA professionals.

Sequencing of HIA steps

Review of guidelines and HIA reports themselves reveals confusion about which steps of the process need to be carried out before or after others. This is particularly a problem with archaeological sites where archaeological reconnaissance survey and preliminary site evaluation may be recommended at the scoping stage. Again “a limited reconnaissance survey and site evaluation before planning the baseline data collection phase” may well be required, with the possibility of even further investigations at a later stage. Archaeological field

evaluation is a pivotal part of the baseline study and further work may form part of the mitigation plan. Following this kind of schedule, therefore, a potential site could be “investigated” three or four times during an HIA.

Shared vocabulary

It is critical that HIA practitioners use an agreed upon and shared vocabulary to describe basic terms and concepts, particularly when discussing kinds and nature of “impacts” and the “acceptability” of impacts on cultural resources. Terms should be clearly defined at the beginning of every HIA report, based on terms agreed upon by the discipline and used consistently. An assessment based on vague and inconsistent terminology has no internal integrity and can neither achieve its purpose nor help build the wider body of HIA research.

HIA and the community

The role played by community consultation varies widely in HIA approaches. In some cases only passing reference is made to the need to seek stakeholder input, usually in identifying resources in an area. At the other extreme, some approaches state that no mitigation should be considered unless it has total stakeholder support, and that the best mitigation is that proposed by stakeholders (Rogers 2011). Clearly, the ideal lies somewhere between, once again highlighting the role of HIA as a tool for negotiation and settlement.

When to do an HIA

In most western countries the assessment of potential impacts on culture and heritage is a requirement of the existing EIA system, based on consultant input adhering to strict guidelines and reporting requirements. However, there are many parts of the world where EIA does not include consideration of heritage at all and HIA occurs in different contexts. These may include HIA as a donor agency requirement following relevant safeguard policies, at the request of the

UNESCO World Heritage Centre to address issues arising at UNESCO World Heritage properties or as a result of NGO or private sector initiatives in response to proposed urban or rural redevelopment proposals.

The latter has resulted in the development of new and diverse applications of HIA to deal with “real world heritage problems” such as HIA of adaptive reuse proposals for historic properties; to evaluate the sustainability of tourism at heritage places; and impacts on intangible heritage resources and traditional “ways of life” and “spirit of place.” Importantly, HIA has been adopted reflectively to assess the impacts of proposed or ongoing heritage conservation projects, which often pose a grave threat to heritage.

HIA now and in the future

This development of varied approaches and methods of HIA for different agendas has enriched the practice but has also resulted in methodological confusion and mixed standards of implementation and reporting. Guidance to help deal with this situation is increasingly available and increasingly sophisticated including international principles, guidance from international donor agencies and banks, guidance for specific types of heritage, from countries where HIA is part of the EIA process, and for specific types of development. The targeted users vary from site managers to consultant practitioners, government heritage authorities, and funding banks. All state the importance of safeguarding heritage, or at least of tangible heritage, and urge the inclusion of heritage into the formal EIA process.

Looking at these adaptations of HIA informs us regarding the current state of practice and reveals a great deal about the potential of the methodology and how it can be further developed. At the national and regional levels worldwide work continues on setting standards and procedures for HIA. ICCROM has been focusing on the development of methodology for HIA in its many applications, working for example in Asia with the Asian Academy for Heritage Management (AAHM online) and the World Heritage Institute for Training and Research in Asia and the Pacific (WHITRAP) on training and manuals for global

use. Similarly, ICOMOS has prepared guidance specifically for the use of HIA at World Heritage properties (ICOMOS 2011) and the World Bank continues to refine their safeguard policies using impact assessment procedures and approaches.

In recent years there has been a growing interest in developing the theoretical underpinning of HIA. HIA can be seen as one of a suite of tools that help support more sustainable decision-making and planning, but there is a wide range of views as to how effective it can be from a theoretical point of view. HIA like EIA was built upon the rationalist model that if we provide better and more information to decision makers then they will inevitably make better and more rational decisions. This is clearly contrary to political and social reality. Current research and critique of HIA is focusing on these issues and on how to expand, reinforce, and develop the scope of HIA (Roders and van Oers 2012).

The strengths of HIA

HIA is a powerful methodology because it employs systematic examination of the full range of potential events and outcomes, combining overview with detail. It integrates heritage values and authenticity with development visions, engineering works, and stakeholder input to engage with the bigger picture. Most importantly, its findings and recommendations cannot be easily dismissed as just opinion, bias, or selective discussion.

Every HIA generates an expanding database of known and newly discovered heritage resources and galvanizes public interest in heritage under threat (Rogers 2011). At the same time the HIA process can add to asset value, not just for developers, but also by identifying and evaluating previously unknown or unacknowledged heritage items and increasing the value of heritage sites. An HIA is not just for protecting sites, but can also be used as a vehicle to provide benefits that enhance and improve them.

SEE ALSO: Cultural Resources Management; Heritage and Society; Heritage Management; Value or Significance

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Authorized Heritage Discourse

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The term “authorized heritage discourse” (AHD) was introduced into the field of heritage studies by Laurajane Smith in her now widely cited monograph *Uses of Heritage* (Smith 2006). Its introductory chapter, “The Discourse of Heritage,” sets out a cogent argument that heritage discourse and practice have been and continue to be shaped by a particular “discursive practice” that determines the way heritage is thought about and practiced.

In the 1970s and 1980s the discipline of archaeology had become subject to a wave of critical self-reflection. It came to be recognized that “the work done by archaeologists is not neutral, self-contained or objective”: archaeology involved a process of writing about the past in the present, and inevitably the “interpretation of the past is affected by present ideology” (Shanks and Tilley 1987). Since the 1980s this understanding of the discursive nature of archaeology has encouraged further interrogation of the nature of what Shanks and Tilley identified as the ideological construction of this “linguistic medium.”

More recently, archaeology’s claim to stewardship has been questioned in relation to debates concerning heritage. Archaeology, Waterton and Smith argue, is one of the “forms of knowledge [that have] become privileged in maintaining authorized historical and cultural narratives” and in this capacity has gained “a certain degree of power to influence particular cultural and social debates and meanings” (Waterton and Smith 2009, 17). The effect of such discourses is to “maintain the legitimacy of elite history and the social hierarchies that flow from this” and to deny the claims of “subaltern groups” that offer a different sense of historical and social experience (Waterton and Smith 2009, 17). More broadly, these dominant western assumptions and conclusions have come to be embedded, through

UNESCO conventions, in the management of heritage internationally, from the Venice Charter of 1964 to the World Heritage Convention, which was adopted by UNESCO at the General Conference in 1972.

Since the publication of *Uses of Heritage* in 2006, reference to AHD has become pervasive in debates about heritage and in the analysis of heritage practice and management at both global and national levels. It is therefore useful to begin with Smith’s starting point, which was that certain objects, practices, and ideas of the past only become “heritage” when they are so defined. This view of heritage involves two further related assumptions: that the definition of heritage is at all times dependent upon an “authorized discourse,” typically as articulated by an “authorized body” that gives specific heritage meaning to particular places, objects, and practices; and that this discourse has historically been dominated by assumptions derived from “western” heritage traditions. This interpretation of heritage practice therefore problematizes “heritage” as a field of political power, typically monopolized at the nation level by national governments in conjunction with owners of “elite cultures” and “experts” and internationally by and through global institutions.

The identification of AHD also contains a demand for the recognition of global cultural diversity in heritage discourse and practice. Second, it directs critical attention to the power conferred upon heritage “experts” to determine what heritage is and thus to deny the right of “the subaltern” to offer alternative interpretations. Third, if AHD is construed as a critique of any formal “authorized” attempt to define and predetermine heritage practice and, implicitly, as an advocacy for recognizing the possibility of an infinite degree of diversity in what constitutes heritage, its targets along both these lines can extend infinitely.

The critique exerted by AHD reflects a broader shift in western intellectual practice as well as in global geopolitical relations that took place in the latter decades of the twentieth century. There is in the first place an obvious debt to the

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work of Michel Foucault, to critical discourse analysis, and, more broadly, to the insight of postcolonial theory, which has influenced the direction of western research in the social sciences and humanities since the 1970s. Already in the 1980s, what was then referred to as “the dominant ideology thesis” had emerged as a critique within heritage discourse (Abercrombie, cited in Tunbridge and Ashworth 1996, 47). Employing Bourdieu’s concept of “cultural capital,” which posits that, typically, “governments or ruling elites will project a message legitimating their position,” the dominant ideology thesis held that heritage interpretation was of obvious interest for “government or ruling elite appropriation,” given its the significance in the definition of national identity (Tunbridge and Ashworth 1996, 48).

At the same time, dissatisfaction with the dominance of the Anglo-western interpretation of heritage and heritage practice at a global level reflected developments in international relations (Akagawa 2014). The early UNESCO conventions designed to define, promote, and safeguard heritage of outstanding universal value, were seen to reflect an exclusively western European intellectual tradition (Akagawa 2014). This western idea of heritage was seen to originate in the writings of John Ruskin (1819–1900) and in the activities of William Morris (1834–96) and of the Arts and Crafts Exhibition Society, which the two of them founded in London in 1887, although longer lineages can be suggested (see also Akagawa 2014). This, however, did not prevent nonwestern states from adopting the principles of the World Heritage Convention into their own national heritage frameworks. For newly constituted postcolonial nations in Asia and Africa, UNESCO’s recognition constituted an important element in international and internal recognition and enhanced the significance of emblems of national identity, reinforcing various processes of national consolidation. Nevertheless, the convention’s criteria for determining what could gain international recognition as “heritage” gradually came to be recognized as discriminatory of nonwestern assumptions and practices, while, within nations, emerging democratic processes also liberated a desire for the recognition of regional and local-community identity and for agency in making heritage decisions.

In the course of the 1990s, debates within UNESCO were gradually pointing to a more inclusive approach to heritage, influenced by awareness of alternative approaches. This tendency was manifested in a number of important enactments, such as the Recommendation on the Safeguarding of Traditional Culture and Folklore (1989), the Living Human Treasures protocol (1993), and the Proclamation of Masterpieces of the Oral and Intangible Heritage of Humanity (1998). The claim for recognition of greater diversity in official heritage discourse enacted by UNESCO was finally recognized in 2001 through the adoption of the Universal Declaration on Cultural Diversity. In 2003 this declaration paved the way for UNESCO’s Convention for the Safeguarding of Intangible Cultural Heritage (ICH), officially adopted in 2005. As Akagawa (2014) notes, however, even then, advocates of an enlarged conception of heritage, notably led by Japan and by UNESCO’s Japanese director at the time, Koichiro Matsuura, initially found little support.

The 2003 ICH Convention significantly broadened the concept and the parameters governing the practice of heritage in the context of UNESCO. It determined that practices, representations, expressions, knowledge, skills—as well as the instruments, objects, artifacts, and cultural spaces—needed to be recognized as “heritage” by this global institution—and, by extension, by its states parties. Most importantly, as later detailed in its operational directives, it emphasized the central role of “community” as integral to the entire process of heritage identification and nomination by the state party.

It could thus be argued that a central criticism of AHD has been largely addressed within the peak international heritage body, whose guidelines influence much national practice. Indeed, Askew (2010) has argued that the AHD case, applied to the current state of heritage discourse, is exaggerated, claiming that “Smith’s uncompromising conclusion about the alleged persistence of the Authorized (Eurocentric) Heritage Discourse ... is belied by the dominance of non-Western practices listed as intangible heritage as well as the transformation of the World Heritage List itself and the influence of non-Westerners in key positions of the bureaucracy” (Askew 2010,

32). In any case, Askew argues, advocates of the AHD critique “misread the character and extent of UNESCO’s power, since it is with the nation-states that the capacity for innovation and oppression ultimately lies” (2010, 32).

While this argument (which effectively repeats the case earlier put by Tunbridge and Ashworth against the proposition of a dominant ideology thesis) may have legitimacy at the international level, Smith’s conception of AHD is much broader. It relates equally to the role of national governments in determining heritage practice at the national level and explicitly applies to all the bodies and experts involved in articulating authorized discourse. In the burgeoning literature on the implementation of the 2003 ICH Convention, this concern is clearly manifested. Although the concept of “intangible heritage” has made it possible for nonofficial heritage claimants to make a case for being recognized, recent literature nevertheless points to continuing obstacles in gaining official recognition that local-community groups face (Smith and Akagawa 2009; Akagawa and Smith 2018). Furthermore, as Askew (2010) also points out, the very framework established by UNESCO requires in the first place that non-formal groups must first gain the imprimatur of national governments, which are the only bodies entitled to submit nominations to UNESCO and its various “expert” committees.

Thus, through its own mechanisms and through the related activities of its states parties, UNESCO not only continues to accord authority over the “regulation and the legitimization of group identity but ultimately imposes interpretation on what ‘community’ is” (Waterton and Smith 2010, 12). Smith (2015) has concluded that all the signs indicate that the 2003 Convention is still overly dependent on AHD and that the addition of intangible heritage has done little to challenge the dominance of western assumptions concerning the universal values that underlie heritage. Rather, it has merely been “treated as another concept to be tacked on to existing definitions ... as something ‘special’ to certain non-western groups, rather than as something more universally applicable” (Smith 2015, 138). What is still required, she argues, is “a framework that privileges the community/sub-national orientation of intangible heritage” and, in the

first place, a recognition that “all heritage is intangible” (Smith 2015, 141).

SEE ALSO: Experts and Stakeholders; Faro Convention; Heritage: Nonwestern Understandings; Heritage and Policy; Heritage and Politics; Heritage and Value-Based Approach; Plurality and Multivocality; World Heritage Sites Designation

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Community Heritage

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Community heritage (CH) research explores a specific community's relationship to its past, and usually to some notion of place. CH projects are designed to be both collaborative and inclusive; they thus document often diverse narratives about a community's history, the nature of its collective identity, or its remembered experience relative to some larger historical event. Community heritage projects are rarely interpretively neutral; they aim to tell untold stories, create civic unity, increase visibility, or raise awareness. They are frequently undertaken in regulatory contexts in which policy frameworks and economic development agendas form a powerful backdrop for how and why the project is undertaken, and what will be done with the results. Community heritage projects can be conducted by scholars from academic institutions, or by practitioners representing a range of government agencies and civic organizations. Many are very grassroots in their inception and structure. Interest in community heritage extends well beyond archaeology as a discipline, and so engages archaeologists in a rapidly growing and wide-ranging professional discussion that attempts to define community heritage as both a concept and a research practice. Other disciplines and professions involved include public historians, geographers, folklorists, or historic preservationists working for museums, heritage organizations, government agencies, and descent communities. Finally, community heritage projects are increasingly found all over the globe, and the resulting professional discussion is commensurately diverse and richly comparative. The examples cited below are intended to give a sense of this geographical range.

This entry describes "community heritage" projects, research trajectories, and theoretical discussions that explore the ways in which a specific community defines its connection to both

past and place. It does not cover "community archaeology," which is a distinct practice described in a separate entry (see HERITAGE AND COMMUNITY ARCHAEOLOGY), although many community heritage projects include an archaeological element. Nor does this entry address work done with local communities who are affected by their proximity to officially or externally designated "heritage sites," in the contexts of tourism, site stewardship, physical displacement, degree of cultural affinity, or other impacts. These three separate kinds of endeavor do however share a recent intellectual history, growing from the intertwined developments over the past three decades of national and international heritage industries, and postmodern critiques of a series of related disciplines from anthropology and archaeology to history, geography, folklore, and sociology. Practitioners involved in all three areas often move from project type to project type, and increasingly read and publish across these disciplinary and methodological lines.

The growing interest in community heritage among archaeologists represents a return to the idea that local knowledge has validity, after twentieth-century repudiation of local knowledge in preference for more objectified and objectifying definitions of a "scientific" archaeological practice. At least three trends have led this return: increasing demands for inclusion and authority by indigenous groups in several colonialist and postcolonial contexts, the rise and intellectual maturation of historical archaeology globally, and the increasingly sophisticated cross-disciplinary literature on the nature of "heritage" itself. The shift is also part of a larger renewed interest in all aspects of the local: an exploration of local scales of human social organization and lived experience as opposed to larger ones. In particular, community heritage research feeds into a growing body of research that sharply problematizes the relationships between localized and localizing social forces, and broader national or global sets of institutional structures, identities, and power relations.

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Community archaeology projects frequently provided the critical intermediate step to draw archaeologists into community heritage (Little and Shackel 2014). They offered both an intellectual framework and a methodological platform. Created for a wide range of reasons, conducted in a variety of ways, and occurring all over the world, these projects have made archaeologists key participants in the development of the community heritage discourse. But community archaeology can also be seen as the context in which many archaeologists first came to grapple with the concept of community heritage, both as a subject for study, and as a broader field of practice in which their own work took place. For a detailed discussion of these challenges to community archaeology in grappling with the nature of community in a series of examples from South Africa and Zimbabwe, see Chirikure and Pwiti (2008).

The most profound impact of this has been on the archaeologists themselves. It has challenged their notions of what both “community” and “heritage” mean, and has created cracks in their understanding of what they do, and what their work means, and to whom. These cracks can be explored as a series of fundamental questions for archaeologists to ask themselves.

What is “community”?

By far the most trenchant critiques of community heritage research coming from practitioners themselves have been aimed at uses of the term “community” (Waterton and Smith 2010). Oversimplified assumptions about the internal homogeneity and shared identity of any given community are seen to stem from romanticized, nostalgic, and ultimately elitist notions of the concept. This fails to take into account the presence of internal diversity, the contested nature of community identity, and the power relations that shape social interaction within the community itself, and between it and the larger social and political context in which it exists. Such critiques are not new, and draw heavily from a larger social sciences literature.

These powerful critiques have led community heritage research towards more nuanced understandings of the ways in which communities, however defined, interact with, articulate, build and transform notions of heritage. Assumptions of homogeneity have given way to analyses of internal diversity, and the contests between and among community constituencies. Public discussions about defining heritage and the meaning of the past are explicit components of more recent projects. Communities are increasingly understood as inherently dynamic, and their ongoing processes of change include redefining what counts as heritage, and how individuals are connected to that heritage. Many examples of the tensions between communities and the professional heritage practice in a variety of European contexts can be found in the compendium *Between Imagined Communities and Communities of Practice* (Adell et al., 2015).

What counts as “heritage”?

In this context, the second fundamental question has been about the nature of heritage. In many ways, this discussion has been driven by increasingly problematic encounters between archaeologists and others conducting community heritage research, and heritage management policies and regulatory guidelines, particularly those with a list-based approach, such as the UNESCO World Heritage List, or the National Register of Historic Places in the United States. Communities often identify as significant many places, sites, and structures that do not match the formal criteria defined in such classificatory systems. David Morgan and colleagues recount particularly trenchant examples of this gap revealed by surveys of perceived losses caused by the devastation of Hurricane Katrina in 2005 (Morgan, Morgan, and Barrett, 2006). Furthermore, communities and practitioners alike characterize as “heritage” many more aspects of shared identity than archaeological sites, architecture, or monuments. And as with the definitions of “community,” “heritage” is now commonly understood to be contested, dynamic, and always under construction. Perhaps even more importantly for the study

of community heritage itself, heritage is understood to be something actively used by people to define and construct sustainable notions of “community.” Three ideas underpin this expansion of what counts as heritage—intangible heritage, place and landscape, and the nature of participation.

The label “intangible cultural heritage,” although the phrase is not used universally, and has its own complicated developmental history, can mean the simple inclusion of non-material practice that local people consider integral to their collective identity: performative arts, local narratives, local calendars of events, and locally held and communicated bodies of knowledge about myriad aspects of daily life: livelihoods and occupations, medicinal practices, religious rituals, children’s play, foodways, and so on. The labeling of such practices as “heritage” inevitably emphasizes heritage as something that is alive, and which must be performed to be maintained, rather than being only an inventory of unaltered buildings, sites, or structures to be preserved in perpetuity. This performative and commemorative approach to culture and identity positions community heritage projects and research as relevant in the present and to the future. Performances of what is inherited from the past tie people to places, pass on specialized knowledge to newcomers and children, distinguish insiders from outsiders, and provide the canvas on which different community members paint their agreement, opposition, exception, and conflict. Communities also use these performances to edit the connections between past and present: to choose what is remembered, how, and what is forgotten, as (for example) research with Inuvialuit and Maori communities have shown (Lyons and Marshall 2014).

Identifying such practices as a category of heritage can lead to them being catalogued, inventoried and officially listed, and this can introduce new debates over authenticity or claims of cultural primacy. It can constrain the very dynamism and situated nature of the practice that makes it work as this kind of living heritage. Li’s study of this interactive process between heritage practitioners and local communities in Chinese villages documents exactly this tension, as well as the creation of entirely new “communities of knowledge production” in the process (Li 2014).

Community-based heritage research also dissolves any hard and fast dichotomy between “tangible” and “intangible” heritage and exposes the links between the two. Notions of heritage that document and define this interconnection are supported by approaches that use place and landscape as dynamic social practices. These efforts borrow from a well-established archaeological interest in cultural landscapes as a more inclusive analytical frame of reference for individual sites and features, as well as being a subject of scholarly study in its own right. They have been reinforced by relatively recent heritage policy adaptations of the landscape framework for management purposes. Community heritage projects regularly explore the relationships and synergies between a given community and its collectively defined physical setting.

How do we do these kinds of projects, and what counts as results?

The ideas behind community heritage research also challenge the notion that a deepening of local or even regional “community” involvement in “heritage” can be accomplished merely by increased public outreach (for instance, by increasing site visitation at officially recognized heritage sites). Such assumptions betray an “assimilationist” mindset that assumes the primacy of officially recognized heritage for everyone (Waterton and Smith 2009, 12) and fails to recognize the significance of other sites, alternative narratives, and more diverse identities.

For that reason, as well as because of the conceptual reframing mentioned above, the development of new or revised methods and procedures have been an integral part of the development of community heritage research. Some of the broader reconceptualization is specific to the archaeological or heritage disciplines, but much is inherent in collaborative or participatory community research done by any discipline. The adaptation to these methodological, analytical and interpretive changes has focused on three core challenges: (1) integrating the new types of data and modes of analysis (particularly those documenting less tangible heritage or drawn

from visual, textual, or oral sources) with conventional archaeological science; (2) modifying older methodologies or developing new ones, so as to accommodate or support multivocality, inclusivity and collaboration; and (3) articulating research between established, “official” heritage management frameworks and alternative (and multiple) concepts of heritage authenticity, significance, and integrity as defined by community members. Meeting these challenges has for many archaeologists redefined research goals and outcomes, such as the expected results of community heritage research, and has raised the question of in what way it is “research.” Such questions go well beyond the notion of “applied science,” and feed into larger discussions of decolonizing archaeology and other Western social sciences.

Community heritage projects require shared authority as well as multivocality. Their goal is not necessarily a single narrative nor to “test” oral traditions and local knowledge against archaeological analysis or heritage presumptions. In CH projects, the community is not a source of data but a set of collaborative research partners. Research methods have to be designed to elicit not just facts, but also values, opinions, judgments, or statements of significance, and they must work with both consensus and diversity. Sarah De Nardi’s work in Italy is a powerful example of this kind of work (De Nardi 2014). There are difficulties in dealing with such diversity. CH research risks creating fixed categories or authoritative narratives from what had been fluid, dynamic, and localized interactions. Furthermore, what should the heritage practitioner do when confronted with stories that a community does not want to tell, because they are perceived as unflattering, or dangerous?

Considerable effort needs to be placed in CH projects on embedding full community participation—community consultation, input, and collaborative decision-making—throughout the entire project, from initial research design to final outcomes. These efforts have required methodological borrowing from the social sciences, notably of rigorous assessment tools. But finding better ways to define and measure participation, to record and document project data transparently and accessibly, and assessing project impacts, outcomes, or effectiveness, are

new methodological needs only beginning to be addressed.

Newer technologies have also played a part in this methodological development. Participatory GIS, social media and web-based digital media provide new platforms for achieving widespread participation and dissemination. They have proved particularly useful for articulating a community’s understanding of its heritage with official heritage policies or protocols, for instance through their creation of alternative maps and narratives. Perhaps even more powerfully, these same methods have been used to create “virtual” restorations of sites, buildings, neighborhoods, or entire communities that no longer exist as physical places, as in the website that made visible Rosewood, an African American town in Florida destroyed in a 1923 race riot (González-Tennant 2015). Social media also become an ever-more diverse platform for contestation and alternative interpretation, circumventing the heritage expert’s narrative control and creating a much more fragmented realm of exchanges, enabling for example what Morgan and Pallascio describe as “remediation” (Morgan and Pallascio 2015, 261).

These methodologies have engendered their own critiques and challenges, however. Principal among these is their highly technological nature. While access has widened (but is by no means global), authorship is often still restricted to experts, or at least mediated through them. Their flexibility and open-endedness can create significant public expectations of access and currency that must be met by those maintaining the databases and websites. Making these aspects of community heritage projects sustainable over the long term has become a significant challenge, particularly for locally supported and grassroots projects.

The discussion about how to do community heritage projects extends to the question of what counts as “results.” The present author’s 12-year-long community mapping project in Levuka, Fiji (Purser 2012) ultimately succeeded in having the community’s version of the town’s character accepted as part of the site’s nomination to UNESCO’s World Heritage List, but ultimately it was the process of creating the map, rather than the map itself, that was considered most valuable by the community members who

participated. Archaeologists are accustomed to a more finite project with a concrete result, generally in a “site report.” But community heritage projects often have goals well beyond the production of a documented narrative of local heritage: for example, to raise visibility, to help an underrepresented group have its voice heard, to strengthen social unity and connection to place, or to develop a sense of shared heritage. In this context, some argue that community heritage projects should be seen as process-driven, rather than product-driven, and that the doing of the project is itself a main outcome (e.g., Little and Shackel 2014). This approach puts even greater emphasis on questions of authorship, sponsorship, and above all, sustainability for such projects over time. It raises again the questions of how CH projects serve any larger intellectual inquiry into the nature of community heritage as a subject for study, and how insights gained from that study can feed back into the design of future projects.

SEE ALSO: Inhabited Landscapes; Memory; New Materialisms; Plurality and Multivocality

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Conservation Plans

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A conservation management plan sets out the value and significance of a heritage site and how that will be retained in any future management, including in terms of use, alteration, or development (see CULTURAL RESOURCES MANAGEMENT and PLURALITY AND MULTIVOCALITY). Such plans are based on a thinking process that puts the way people value heritage together with technical conservation methods. The process of conservation management planning is central to values-based heritage management (HERITAGE AND VALUE-BASED APPROACH).

A plan may be prepared in order to help manage change (for example, in support of an application for new work or development), to underpin routine cultural resource management, in support of fund-raising or grant applications, or as part of an application to inscribe a site in a register. In relation to archaeology, plans are often prepared to inform the management of archaeological sites, and the discipline of archaeology can play a significant role in the planning process.

Although the majority of plans have been prepared for historic buildings, sites, landscapes, or larger heritage items such as ships, the values-based conservation planning process is equally applicable to any kind of heritage, from an individual object in a museum to a large urban conurbation (see URBAN ENVIRONMENTS). Conservation management plans are closely related to other kinds of heritage plans, such as World Heritage Site Management Plans, conservation master plans, heritage management plans, and parks management plans.

Contents of a values-based conservation plan

Although a plan is usually presented as a written document, the critical factor is not its format or length, but the heritage thinking process that underpins it. The steps in the planning process are presented next.

Understanding

The better a site is understood, the easier it is to articulate its value and to manage change in an informed way. The elements that make up the understanding of a site can include its history and how it has changed through time; and these elements draw on oral, documentary, and archaeological evidence, its component elements (e.g., landscape elements, collections, buildings), and its current management and designations. As that information can be extensive, appendices, gazetteers, or databases are often used. Archaeological information is critical to this part of the plan and may cover buildings or landscape archaeology, or the application of analytical techniques such as stratigraphy, phasing, and typologies in order to understand how a site has changed through time. This section can also include information about communities linked to the place and about intangible heritage, memory and remembrance (see MEMORY AND REMEMBRANCE), and traditions—all based on oral history and community consultation.

Assessment of value and significance

The core of the conservation plan explains why the heritage is of value and to whom. It is based on the understanding set out above, and then informs the later policies.

Conservation plans normally explore two kinds of values:

- **Designation values.** These represent the reasons why a site may have been designated or protected. Heritage designations are usually based on a specific range of values—typically architectural, archaeological, historical, or scientific—and there may be a requirement for a particular level of significance (e.g., Outstanding Universal Value in the context of World Heritage sites, or national importance for scheduled ancient monuments in the United Kingdom). This can also include natural heritage designation values, and values that relate to any other form of protection (eg registers of historic ships).
- **Wider public and community values.** Most heritage sites are also important in ways that go beyond the reasons for which they are designated. Those values may include amenity values, spiritual values, social or community values, leisure and use values. There may be aspects of the site that are not protected but are important. Those wider values could include the benefits of conserving the site, for example, social and economic benefits. Some form of community engagement or consultation is essential to understanding these values.

Nonwestern values can be included in the planning process (see *HERITAGE: NONWESTERN UNDERSTANDINGS*) whether they are part of the reasons for the designation or part of the wider issues to be taken into account in managing it.

As well as identifying the different ways in which people value the site, many plans also capture the degree of significance of those values. A protected or designated site will usually have special significance at a state, national, or international level. However, some practitioners also provide greater clarity on the relative importance of different parts of the site in order to assist with future decision-making.

Management issues/vulnerability

This part of the plan should explore management issues such as ownership and control, neighbors and local community concerns, deterioration (see *DETERIORATION*), funding, conservation issues,

maintenance and repair, the wider setting and context, commercial activities, interpretation, visitor facilities and management, the different uses of the site, security, staffing or volunteers, presentation, and health and safety. All of those activities have the potential to impact on the value and significance of the site in a positive or negative way.

Policies for retaining value and significance

The policies in the plan should connect value and significance with future conservation, alteration, use, and management. They might cover anything from interpretation to future use, conservation treatments, visitor management, development, maintenance, alteration, security, setting—all informed by an understanding of the significance of the site. There may be generic policies such as encouraging the use of heritage impact assessment in decision-making, as well as specific maintenance or conservation programs.

Implementation and review

Aside from helping with decision-making, the information in a plan can be used in many ways. The research and analysis might inform interpretation strategies or shape the design of new facilities, while the management information can be a starting point for briefing staff, contractors, or partners. The process of involving stakeholders may have benefits in its own right, while a plan also provides a historical record of how and why decisions were made.

As knowledge of a site grows or the management context changes, a plan may become outdated and it may be helpful to review it.

Plans can be used in conjunction with heritage impact assessments (HIAs), which explore the impact of a specific development or plan of work on the significance of a site and looks into how any negative impacts can be mitigated or avoided. Where a plan already exists, a HIA can draw on much of the information in the plan.

Stakeholder engagement

Understanding how different stakeholder groups value a site and feel that it should be managed

is central to the planning process. While a site may be protected for some values—such as its scientific or archaeological value—different community groups may see the site in different ways. Understanding their perspective, including its nonwestern values, is the first step in identifying potential areas of conflict and in working toward shared goals.

Origins and development

Values-based plans have evolved out of traditional site management planning.

General management plans have long been a part of best practice in parks management services in the United States, Canada, and Australia (National Park Service 2006). Generally, such documents set management objectives and then define how they will be achieved; but, for archaeologists and other site managers who work with diverse communities, such as Aboriginal, First Nation and Native American groups, there has been a growing realization of the importance of plurality and multivocality (see *PLURALITY AND MULTIVOCALITY*) in cultural resource management.

Many of the heritage charters that guide heritage decision-making in a European context, for example, the 1931 Athens Charter for the Restoration of Historic Monuments or the Valetta Charter for the Protection and Management of the Archaeological Heritage, make brief references to significance in decision-making, but it was the Burra Charter (Australia ICOMOS 2013) which has done most to reframe this thinking.

Drafted by a group in Australia with experience of both indigenous and European heritage and adopted in 1979, the Burra Charter sets out a process that puts an assessment of significance and value at the heart of conservation management planning and shows how decisions about managing a site should flow from that understanding, as well as from technical conservation knowledge. One of the authors of the original charter developed detailed guidance on conservation planning (Kerr 2013), and such plans have since become a core part of Australian heritage practice. Although originally focused on

European heritage, the values-based process can be applied to any kind of heritage.

In the United Kingdom the Heritage Lottery Fund (HLF) asks for plans to support applications for funding, in order to ensure that applicants understand both conservation and community issues and that their proposals are likely to be sustainable. Plans have now been prepared for a wide range of different kinds of heritage sites, from ships such as the *SS Great Britain* to sites and monuments, churches and cathedrals.

At a global level, World Heritage site management plans are prepared as part of the process of applying for inscription. Such plans explicitly require an understanding of the outstanding universal value of a site as part of the process of management; but they can also refer to the wider ways in which the place matters to people.

The Getty Conservation Institute studied management in four World Heritage sites in order to understand how such plans were developed and used in practice. It showed that, although the site may have been included on the list for its outstanding universal value, in practice site managers needed to respond to a much wider range of ways in which people valued the place, which were often shaped by current issues (de la Torre et al. 2005).

As well as conservation plans, there are now numerous other tools used in values-based planning, including heritage impact assessments, conservation area appraisals, and statements. In association with the Native American Graves Protection and Repatriation Act 1990, plans of action require practitioners to understand the cultural issues associated with the treatment of archaeological remains, while place-making and community engagement strategies such as the England and Wales National Trust's 'Spirit of Place' statements also explore the different ways in which places are valued by people.

Conservation plans remain controversial. Along with an academic literature that is critical of heritage practice, practitioners themselves debate whether conservation is a social or a technical discipline. For some, the preparation of written plans takes resources away from maintaining and managing heritage sites; for others, the time spent in planning is an essential part of the community engagement needed for sustaining sites. Either

way, values-based conservation plans are a practical way of bringing together social and technical approaches to conservation.

SEE ALSO: Conservation; Faro Convention; Heritage and Society; Heritage Planning and Design; Value or Significance

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Countermapping

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Countermapping refers to practices of mapping that are designed to represent indigenous or local cultural landscapes from the inside, which is to say to represent them against the dominant external cartographic practices which are perceived to efface or misrepresent these landscapes. In an archaeological context, countermapping is employed to spatially articulate archaeological remains which have gone unrecognized by governments and corporations to the detriment of local people or to provide local counter-interpretations of officially recognized archaeological sites and arrays of sites.

The term “countermapping” was first used by the environmental anthropologist Nancy Peluso (1995) to describe the way nongovernmental organizations (NGOs) working with forest-dwelling groups in Kalimantan, Indonesia, adopted cartographic techniques, ordinarily the domain of forestry companies and state resource bureaus, in order to record the location of key food resources, ritual sites, story and song locations, and other key loci in the forests inhabited by these people. The resulting maps were designed to give local people a voice at the tables where vital questions regarding the fate of the forests were being decided. Other anthropologists working in Southeast Asia helped develop the approach (e.g., Brosius, Tsing, and Zerner 2005; Roseman 2003) and it subsequently joined a plethora of other alternative mapping approaches under labels that include indigenous cartography, participatory geographic information systems (GIS), and autonomous cartography. In the time since Peluso’s early work, digital technologies, including GIS and global positioning systems (GPS), have become widely available and have to a great extent democratized map making. While it is important to acknowledge the existence of traditional mapping practices, in which maps

were and are sometimes inscribed in the dirt, on rock faces, on paper, and other surfaces, digital technologies have been important in allowing these customary forms of mapping to evolve to meet present-day needs. Such needs include the archiving of traditional knowledge and ensuring its availability for intergenerational transmission. These exercises in mapping have been carried out by archaeologists collaborating with indigenous groups (for example, Byrne and Nugent 2004) or indigenous groups autonomously mapping the archaeological terrain in their homelands.

Archaeologists operating in the Global South were mostly slow to appreciate and acknowledge that archaeological remains, even those that were millennia old, were frequently an embedded element of the social landscape of contemporary indigenous dwellers in the same terrain. Where they are manifest at the surface, archaeological remains can be considered continuous with a whole universe of marks that we learn to read and navigate in the course of our daily lives and in the context of our cultural world view (Bradley 2002). The participation of archaeologists in countermapping projects has been underwritten by the increasing subtlety of the profession’s ability to engage with the experiential materiality of past life worlds, as seen in the phenomenological archaeology of Christopher Tilley (2010), and in Tim Ingold’s “dwelling perspective” (Ingold 2000). Archaeological traces, while deriving from past behavior and events, are continually recycled back into the contemporary social environment and they can be said to be “regrown” in the lived environment of each new generation. It is in order to demonstrate the truth of this to wider audiences that so many indigenous groups have embraced countermapping practices.

The path-breaking ethnocartographic practices of Peluso (1995), Roseman (2003), and others working with tropical forest dwellers in Southeast Asia demonstrated that forest areas which previously had been depicted on official maps as culturally barren were, in reality, intricately inscribed cultural landscapes, where former swiddens were regarded as storied historical sites, where individual trees were often

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known by their own names, and where ridges and gullies were mapped with the territories of spirits and gods. An example of this kind of sensibility being brought to archaeological counter-mapping was Rodney Harrison's collaborative work with the Muruwari Aboriginal people of northwestern New South Wales, Australia (2004; 2011). Focusing on the continued significance to the Muruwari of a now-abandoned campsite they had occupied from the 1870s to the 1940s, Harrison showed how during their periodic visits to the site, the Muruwari sometimes had visions of spirits in human form. Artifacts found there became "extensions of long-dead relatives: powerful, troubling and at times problematic" (Harrison 2004, 205). When visiting such sites, Muruwari people sometimes picked up flaked stone artifacts and rubbed them on their bodies. One Muruwari woman explained, "when you're rubbing the stones over your skin you can get the feeling of ... you sort of get the feeling of the spirits coming into your skin somehow or another" (Harrison 2004, 199). The propensity of these artifacts to not merely evoke the dead relatives who had used and sometimes made the objects but to *presence* them is something a purely archaeological recording of the campsite and its surface assemblage could not hope to reveal. Only by being actively engaged in such mapping or by conducting it themselves can such indigenous people convey the real meaning these places and landscapes have for them.

Thomas and Ross (2013), discussing the integration of archaeological and indigenous knowledge datasets at an Aboriginal stone arrangement site in southeast Queensland, Australia, refer to the way sites such as this are "continually being reformed and resurrected" by their cultural custodians. Unhappy with the way previous exercises in archaeological counter-mapping had been constrained to work with two-dimensional maps, which inevitably fix the cultural landscape at a particular moment in time, they used the Web-based tool Prezi, to allow the viewer to move through the landscape in the way it is believed Aboriginal travelers did in past times. Being Web-based, the "maps" they have created can be updated and modified according to the changing conceptions of the Aboriginal traditional custodians and in line

with the acquisition of new archaeological data (Thomas and Ross 2013, 234).

It is worth remembering that the first exercises in counter-mapping, conducted in the 1990s, had a specifically decolonizing objective. Indigenous people and archaeologists who have worked with various forms of counter-mapping have been conscious of the way archaeology, as practiced in settler colonies and in the Global South, has involved a process of translation in which precolonial archaeological remains are not merely rendered compatible with modern cartographic productions but are made over into state-supported modern ontologies. Reflecting on their work with Mayan communities in Belize and the Mayangna community in Nicaragua, the geographers Joel Wainwright and Joe Bryan (2009) have summarized the downside of counter-mapping in terms of uneven participation in mapping (for example, by indigenous women), its potential to cause internal disharmony among group members with different interpretations of landscape, the risks of causing or inflaming border disputes with neighboring indigenous groups, and, because counter-mapping is often carried out to secure legal recognition of rights to land, the negative effect of the indigenous community's relations with land being articulated as *property*. Nevertheless, in the early twenty-first century, a great deal of creative energy has been devoted to creating an alternative, decolonized space in which indigenous perspectives can be represented in a more-or-less unalloyed form. The technology of 3D digital simulation has had a key role here, resulting in a rapidly expanding universe of online productions, which are difficult to do justice to in a text publication such as this but can be sampled online, for example at Wikipedia's page on the "Indian animation industry" (https://en.wikipedia.org/wiki/Indian_animation_industry, accessed November 27, 2017) and at the Monash Country Lines Archive (<http://artsonline.monash.edu.au/countrylines-archive/>, accessed November 27, 2017). As a result of these developments, there has been a blurring of the boundaries between indigenous archaeological site and landscape representations, digital storytelling, and digital animation designed for revitalizing indigenous languages (<https://rising.globalvoices.org/blog/2016/03/20/series-of-animated-stories->

revitalise-indigenous-languages-in-mexico/, accessed November 27, 2017).

In the days before digital mapping, the paper maps in existence were mostly produced and policed by state authorities and were widely held to be authoritative. The aura of completion that they possessed explains the anxiety of local groups not to be “left off the map,” whether through the ignorance or the strategic intent of official cartographers. Digital mapping, particularly where it is Internet-based, open source, and community-based, has exploded the truth claim of the paper map. A new conception of maps as fluid and democratic has gained currency in “mainstream” (i.e., non-indigenous) society. During the 2010s, open source mapping that aggregates spatial data collected by volunteers, the most prominent example being OpenStreetMap, has resulted in a vast expansion in the number of community mappers, most of whom are not from marginalized or indigenous groups. A number of NGOs now promote and facilitate community mapping. For example, the NGO “historypin” (<https://www.historypin.org/en/>, accessed November 27, 2017) operates a website where anyone can upload and maintain collections of historical photographs, videos, and stories, which effectively act as a mapped, digital platform for place-based public history.

Understandably, much of the countermapping activity in archaeology has been concentrated in the area of archaeological heritage recording and conservation. This relates to the fact that government heritage agencies were collecting spatialized data on local peoples’ heritage sites long before techniques of countermapping became available. Many countermapping initiatives have thus been motivated by a concern to correct what were seen to be distorted or partial inventories and official mappings of local heritage. Two factors are, however, likely to impede the emergence of a universal open-access inventory of archaeological heritage sites. First, the digital maps of these inventories that are maintained by government heritage agencies may be “open access,” but the *entry* of site data onto them is usually restricted by legislation, meaning that only those sites that meet defined criteria and significance thresholds are included. Second, indigenous groups concerned with ensuring that their cultural knowledge is not

publicized, commodified, and commercialized often either maintain their own “closed” spatial databases or decline to have particular categories of sites and knowledge included on government heritage databases.

The overview presented here charts the spread and mutation of countermapping practices since the 1990s. In this process, in-place archaeological traces have been inscribed on a variety of maps intended for a variety of purposes, most of which have been to do with depicting and defining indigenous cultural habitats. The “countermapping” label may be close to the end of its usefulness, but there is every indication that archaeology—both the profession and the stuff—will continue to be caught up in the technology and cultural politics of mapping.

SEE ALSO: Community Heritage; Cultural Resources Management; Digital Cartography; Environment and Landscape; Heritage; Nonwestern Understandings; Heritage and Community Archaeology; Heritage and Landscapes; Heritage Management; Memory

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Critical Museology

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Critical museology investigates the practices of applied or operational museology and the range of heritage regimes and policies with which it is always entangled.

Throughout its relatively short history, museology has attempted to present itself as an applied discipline based on a body of empirical knowledge, tested presuppositions, and notions of the common good to sustain its hegemony and utility in supporting museums and related heritage institutions. Its seeming intellectual and logical coherency, ethical conviction, and functional certitude, occlude its political operations, strategies, and changing objectives. The hidden epistemological differences that underlie museology's actual heterodoxy of knowledges and the strategies by which specific forms of national and neoliberal expressions of individualism and personhood have been abstracted and essentialized, stand in fundamental opposition to museology's privileged academic and disciplinary claims. Focused on the theory and practice of museum and heritage management, collections and their curation, exhibition and public engagement, what is usually described as museology is better prefixed as "operational" museology. Although presented as disinterested and universally applicable, *operational museology* is always constructed from specific national histories, governmental practices, and political strategies that usually have their origin in the English or French speaking worlds. The briefest analysis reveals that the extensive personal, institutional, intellectual, and citational networks that underlie most museological discourses and practices, far from having universal application and scientific value, originate in the United Kingdom, the United States, Canada, Australia and New Zealand, and are inadequate as both

models for organizations elsewhere, and as intellectual frameworks to describe the plurality of histories, views, and practices outside their national spheres of operational competency. The universalist presumptions of this anglicized or francophone museology excludes other histories of collecting, institutionalization, and mobilization of collections, and their wider integrations into alternative exhibitionary complexes and coexisting hegemonic projects, it also largely ignores the potential of museology as a vehicle for resistance, critical theories, and counter hegemonic strategies.

Operational museology refers to the underlying imaginaries: bodies of knowledge; rules of application; procedural and ethical protocols; organizational structures; institutional relationships and regulatory interdictions, through which collections are assembled, managed, curated, circulated, reproduced, and expanded. *Critical museology* has developed since the 1970s in opposition to the objectivist claims, universalist pretensions, and ideological effects of operational museology. Critical museology investigates the practices of operational museology and the range of heritage regimes and policies with which it is always entangled. In addition, critical museology scrutinizes the institutions that support cultural and heritage institutions including their professional organizations; accredited academic courses, systems of internship, mentorship and peer review; and their related conference cycles, seminars, and publications through which institutional narratives and discourses are mediated and regulated.

Epistemological positions

Critical museology is based on four fundamental epistemological positions and includes several methodological principles that guide its application. The deployment of these positions and principles sharply distinguish critical from operational museology and enables it to sustain reflexive and critical analysis, destabilize

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essentialist assumptions, and propose ways to transform organizational practices and diversify exhibition genres. It constitutes therefore, both a method of critical analysis and a means for establishing alternative museological and curatorial practices.

Position one: critical museology treats history as a cultural construction through which intellectual and ideational genealogies and disciplinary and institutional legitimations are constructed, mediated, and reproduced. It sees history as composed of culturally constructed event structures that are traced backwards in time to structure causal and deterministic narratives that claim to explain current institutions and material cultures, including museums, galleries, and monuments, and the defining characteristics and operations of heritage regimes. Museums and heritage regimes are situated within specific political, cultural, and event-based structures and cannot be abstracted or reduced to common sets of generalizations or universalist principles.

Position two: critical museology rejects the notion of the collector as a being abstracted from society and culture through the imputation of their individuality and/or universalized psychological disposition. Neither the individual who supposedly embodies these predispositions nor the drive towards possessive and competitive acquisitiveness can be assumed to characterize the whole spectrum of human behavior. The figure of the collector and the instincts that supposedly motivate their activities, far from representing an aspect of common human nature, are the unique creation of certain types of western art historical discourses and psychiatric and psychoanalytical operations, employed by operational museology to legitimate its field of operations. Collectors and their activities exist in specific social and cultural milieus which inscribe their activities within systems of significations and value, and shape behavior, procedures, organizations, optical regimes, and the mechanisms and aesthetic values that govern their utilization and deployment. The relationship between collectors and their assemblages is always specific and cannot be abstracted and essentialized to legitimate collecting institutions.

Position three: objects have no meaning independent of that which is ascribed to them through language and culturally specific classifications.

The meaning and value of materials, objects, or assemblages is always relational and contingent on a wider social and semantic field of relationships that reject mechanistic views of active knowledge acquisition and transference and its reception by supposedly passive subjects. Knowledges and the communities from which they are derived are active, dynamic and in constant change and transformation. It therefore follows that the knowledges they produce and which museums appropriate, synthesize, and seek to disseminate are never naturally bounded, complete, or definitive, but always in a process of expansion and becoming. Similarly, museum visitors do not simply absorb knowledge as presented, but mediate and interpret it according to their own presuppositions and educational, cultural and political backgrounds. Museum knowledges are therefore doubly mediated, first through the methods by which they are synthesized, and secondly through their differential interpretation by visitors and other interlocutors.

From the above three positions, it follows that the empirical or rationalist epistemology on which western museums have been founded, which governs their operation and legitimates their existence, is fundamentally flawed. Empiricism and positivism while insisting on the intelligibility of reality as perceived through the senses and its amenability through plain description, ignore their inability to apply their own epistemology to legitimate their foundational assumptions. Isolated, outside of its own rules of description and criteria for attributing truth and meaning, empiricism ignores the question of the legitimacy of its own criteria of truth, and therefore, not only severs epistemology from method, but occults its own ideological inflections. Empiricism and positivism hypostatize knowledge of "reality" and in so doing favor a naturalized and nonproblematic theory of meaning.

This leads to the *fourth position* of critical museology that holds that museum authority can no longer be legitimated through reference to a universal and transcendental theory of knowledge that locates meaning as independent of human agency. Neither is it permissible to regard scholars and curators as disinterested observers whose special training allow them to "discover" knowledge and the relationship and significance of objects as expressions of universal truth.

These four positions, fundamental to the process of museological deconstruction, constitute a discipline fully compatible with the epistemologies and goals of postprocessual archaeology, new material culture studies, and critical heritage studies. Furthermore, critical museology is dependent on collaborative and indigenous methodologies that through the juxtaposition of alternative epistemologies, methodologies, and the knowledges they generate, contribute to the relativization of the western categories on which operational museology is based. However, critical museology, unlike some of these, in no way advocates the epistemic privileging of one knowledge system over any other in a manner that would assert a different orthodoxy and its attendant power relations. Instead, critical museology aims, from its observation and intervention in operational museology, to sustain an ongoing interrogation that intends to place museums and related institutions in flux independent of stabilized social conventions and values. In this respect operational museology and curatorial practice provide critical museology with a laboratory in which its commitment to heterodoxy is able to impute disciplinary and institutional change and transformation.

Methodological principles

This relativist epistemology leads to a distinctive, though by no means exhaustive set of *methodological principles* that inform critical practice. The first of these, the acknowledgement of the effects and deployment of agency, is foremost to critical museological work. Institutions do not exist independent of complex, cross-cutting networks of often contradictory and conflicting powers and interests, which provide channels for the projection of agency. Museums are connected internationally through formal and informal and real and digital networks and channels. Digital connectivity in particular engenders relationships and networks that sometimes provoke unexpected professional, political, and personal alliances and antagonisms between different interest groups. Through mediating the agencies expressed and directed through these networks, museums—whether administered by

communities, private foundations, or national or municipal governments—always attempt to synthesize a singular politic of patrimony, which links together collections, monuments, and buildings with a specific territory. These heritage regimes are never static, and the values, interpretations, and political economy which they promulgate are usually contested by different interest groups. So great have these differences become in North America and the Middle East that they have become inflated into “culture wars.” Heritage institutions therefore are always subject to the play between internal and external normative and subversive agencies which lend them their complex, shifting and provisional qualities. Critical museology regards the use of categories like “traditional,” “primitive,” “modern,” “Oriental,” and “occidental” that deny agency in favor of transcendental laws and categories, regardless of their intellectual interest, as lacking analytical use and rigor.

The *second principle*: Critical museology views institutions and the knowledge and cultural creations they generate as part of a wider field composed of other institutions and intellectual and creative positions to which they are related. The operations of one institution or set of practices need be understood in relation to others sharing the same field as well as the position occupied by museum analysts who can never stand outside of the field they explicate. Analysts never play solely an observational or recording role, but actively intervene and unintentionally change the field. The foci, the construction of the field of observation, the questions asked, and the perception of the presence of the analyst, must be recognized as part of the field of study.

The *third principle*: In explicating set conditions, phenomena, or experiences analyses also constitute their antonyms, which are unintentionally produced as a residue of that which falls outside the primary category of investigation. The category of “popular art” is part of the residue from defining “elite culture,” or “nature” consists of the residue from defining culture, and not of an untransmutable and objective category that is the same for all cultures and societies. The construction of mutually dependent extensive and exclusionary binary classifications leads to the categorization and configuration of different types of materials and

artifacts and their institutionalization in different types of museums. In effect, by defining the focus of a heritage regime, policy, or institutional specialism, exclusions, which analytically may be as important as the institutionalized categories themselves, are inevitably generated which require acknowledgement and scrutiny.

The *fourth principle*: Critical museology is never exhausted by the deconstruction of operational categories or the explication of social and political strategies. As terms of the dominant discourses or narratives are effectively made transparent, operational museology strives to retain, reform, and perfect its coherency and authority through adopting new practices and terms of engagement, which it partly appropriates from the findings of critical museology and other disciplines and cultural knowledges. In the last few decades, British and Canadian museology has replaced mechanistic with dialectical models of museum communication; exhibition foci has partly changed from a national to a global focus and this in turn has created new organizational structures for circulating collections and knowledge specialists. Moreover, museums have changed from object to public-centered practices. Nevertheless these shifts imply only changes in the conditions and operations of museums which, whether positive or not, are still required to be subject to ongoing critical enquiry. Such adaptations attest to the elasticity of operational museology's hegemonic functionality and its adaptability to changing conditions, which critical museology is charged to expose and transcend.

These four epistemological positions and four methodological principles distinguish critical museology from other forms of critical museological writing. The new museology developing from critical historical research and the art history of the 1980s, best represented by Peter Vergo, while critical of the operational museology that preceded it, did not develop a method or purpose of its own. More recently, collaborative museology has achieved greater success in articulating its political and disciplinary objectives and in distinguishing different methodologies within it. However, its relationship to indigenous methodologies, especially when it tries to generalize these and engage with their abstraction or reduce itself to subservience to one or other

of them, quickly loses intellectual relevance and credibility. In the first it synthesizes and distracts itself by chasing chimeras, while in the second it reduces itself to a series of practices, divorced from disciplinary legitimation, capable of bridging, but not questioning prior established inter- and cross-cultural conditions and relationships. Collaborative museology, by acknowledging the expression of cultural heterodoxy, supports critical museology but because of its political objective and limited view of criticism, usually falls short of it.

For critical museology, the authority commonly attributed to museums is contingent. Instead of them constituting shrines of truth as an older museology once insisted, it regards museums as agencies of interpretation, which hold the promise of a future possible transformation into forums for dialogue and transformation into open rather than closed institutions.

Open and closed museums

The distinction between open and closed institutions is crucial to the understanding of museums. Closed institutions are those that legitimate themselves through transcendental logics on which universalist laws governing classification, causation, determinism and positive or negative evaluations of categories and actions are maintained. They transform abstraction into actions, which they divide and consecrate as either meritorious or contemptible; normative or censured; good or bad, and thereby delineate the boundaries between acceptable and disparaged dogmas and actions. Their embrace of transcendental logic creates communities holding non-contingent, immutable beliefs that impose limits on interpretation and intelligibility, establishes their exclusivity, and regulates their membership. Open institutions, on the other hand, are distinguished by relativist concepts of knowledge based on their contingent, open-ended, agentive and generative propensities and the nonfixity of ethical and moral principles and actions implicit in their transformation. Closed institutions provide universal and comprehensive security, truths, and life principles while narrowing the space of individual freedoms

and intercultural dialogue, and usually adopt authoritarian forms of organization. Open institutions, on the other hand, develop and receive their vitality through critical dialogue, their incredulity towards the metanarratives and arbitrary establishment of borders and boundaries between disciplines, knowledges and cultures, and their exploration of categories like difference, hybridity, and “creolization.”

The distinction between open and closed institutions allows for an alternative classification of museums in which national institutions, still committed to narrating the history, flora, fauna, and intellectual and aesthetic achievements of the resurgent nation-state form one pole of a spectrum whose opposing exemplar is represented by the contemporary art or critical ethnographic museum. Contemporary art has been defined as a form of critical interrogation, exploration, and expression of contemporary existence which possesses its own museology that shares common foci and aspirations with critical museology. The critical ethnographic or anthropological museum, whose potential is more acutely repressed under western capitalism, is represented by world culture museums and a few municipal and university museums including those of Neuchâtel, Geneva, Tenerife, Santa Cruz, and Vancouver, which actively critique and problematize accepted western categories, classifications and interpretations of the world. Different orientations are not determined by types of museums though university and municipal museums usually have more operational latitudes, but by their curators. Outside the western canon, the growing number of indigenous museums and cultural centers in Australia, New Zealand, Canada, Mexico, United States, and Taiwan have established their own museology which directly supports the work of open institutions. Open institutions are an essential component of the movement to transform museums into multiversities. As developed by Paul Wangoola and Claude Alvares, the multiversity combats western universalist knowledge systems by acknowledging that all knowledges are culturally constructed and should be treated as having identical value and heuristic competence within their field of proficiency. Alvares demands a deconstruction of western thought and the history, institutions, and singular concept of science whose continued

dominance, he argues, dismisses other scientific systems and perpetuates a western intellectual dominance that prevents their economic, social, and cultural development. The purpose of progressive thought, for Alvares and Wangoola is to challenge western intellectual hegemony and, through the multiversity, acknowledge the plurality of knowledge systems. The multiversity is then a series of museum displays that attempt to exhibit different cultural themes according to their indigenous rather than their western categorizations, classifications, and significances that represent a concerted, but only too rare example of a decolonizing process. Despite the recent tendency of some museologists to proclaim a new postcolonial museum age, exhibitions other than those on singular native peoples, cultural resources, and organizational structures have everywhere remained resistant to large-scale transformative change.

SEE ALSO: Experts and Stakeholders; Heritage and Nationalism; Heritage and Politics; Heritage Interpretation; Material Culture; New Materialisms

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Cultural Resources Management

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Closely associated with “conservation” and “archaeology,” “cultural resource management” (CRM) is the suite of legislation, policy, guidance, and professional practices for the management of heritage places. Originally focused on the authenticity of historic fabric, and the preservation of historic places, “heritage” now includes ideas of identity, memory, the intangible, and change. There is now recognition in the West that not everything can be saved and that “change” is both natural and expected. Therefore “heritage management” is now better understood as the ways in which “change” to the historic environment is “managed” to ensure the continuance of “cultural significance.”

Still a relatively young discipline, CRM is the title used in North America, whereas “cultural heritage management” (CHM) is preferred in Europe and Australasia. The effective operation of CRM/CHM relies on archaeology and heritage being part of a defined legal and developmental process. In both the United Kingdom and the United States CRM/CHM is a recognized, largely commercially run professional practice (Doelle and Altschul 2009) usually identified through a step-by-step archaeological procedure to establish the impact of a development on a heritage place and then mitigate its impact. Practice usually includes desk-based assessment, geophysical survey, archaeological evaluation, and modification of the proposed development design or its excavation and publication, known as “preservation by record.” A comparable set of techniques is used for the assessment of the recording of historic buildings in advance of any change to the fabric.

In the United Kingdom “heritage” is a recognized part of the national planning system and developers are required to identify and mitigate

impacts of development on heritage places as a condition of receiving planning permission. In the United States heritage is dealt with at Federal and State levels, but encouragement for individuals and organizations to support heritage preservation is also promoted through the tax system. As a consequence there is an active local and charitable element to preservation in the United States that sustains national and regional heritage places (Stipe and Lee 1988 provides the best overview of the evolution of US preservation practice). However CRM/CHM is not universally applied as many nation states do not include heritage in the development process and do not have a robust heritage infrastructure at national, regional, and local levels. Similarly, for some nation states, such as India for example, heritage is a “living” and omnipresent concept more related to people, tradition, and the intangible rather than something that seeks the preservation of historic fabric.

Origins

Lowenthal argued that the origins of CRM can be traced back to the Classical era (Lowenthal 1985), but also suggests that people have always used the past for the purposes of shaping their particular present, whilst “nostalgia” is a common human trait.

The dramatic social and political changes in nineteenth-century Europe provoked considerable reflection on the past by writers, philosophers, artists, antiquarians, and architects. The movement of large numbers of people from a rural, agricultural to an urban, industrial life created a sense of nostalgia about past lifestyles but fueled concern about increasing physical loss of historic buildings and sites, and this created a desire to identify ways in which change could be managed to either preserve historic places or lessen the damaging impacts on them.

“Restoration” became a key term in ideas about preservation with opposing ideas about the use of new or complementary materials in historic

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sites. The opposing views are best represented by the French architect E. E. Viollet le Duc who proposed using new materials, whilst the English writer, artist and critic John Ruskin considered restoration in all its forms to be dishonest. To Ruskin and his followers (particularly William Morris), authenticity was paramount, reinforced by craftsmanship and the patina of age. Historic remains were to be carefully maintained to prevent greater loss, and repairs were to be conducted using complementary materials. These opposing approaches have shaped modern practice, and can still be seen in current conservation management charters and guidance.

The late nineteenth century also saw an increase in the number of nations introducing legislation to preserve historic places to protect them from change. In the United States industrialization presented an opportunity to reconsider how the country saw itself in the industrial world. Wealthy first and second generation migrants such as J. D. Rockefeller, J. P. Morgan, and Stephen Mather developed an interest in heritage. The recreation of the former capital at Colonial Williamsburg, Virginia, was supported by Rockefeller from the early 1920s, whilst Mather urged the creation of a National Park Service. Similarly there was an interest in the acquisition of heritage assets, with both J. P. Morgan and W. R. Hearst acquiring artifacts and buildings from both Europe and the United States. One outcome was that the City Council of Charleston, South Carolina became the first assembly to introduce planning and zoning regulations in 1929 in order to protect its distinctive colonial architecture and spaces.

As preservation legislation became established, nations created their own lists of nationally important heritage sites and created heritage bodies to manage those lists and sites. Ultimately a particular style of archaeology, repair, and presentation evolved emphasizing the individual site, and the authenticity of its fabric, history, and aesthetic, but presented in a scientific and scholarly manner treating the public as a passive recipient of a national narrative. The preeminence of American and European approaches to conservation ensured that this particular style of conservation management spread across the world through political, economic, and imperial

control and underpins present day approaches to CRM.

The high point of this approach is represented by the Venice Charter (ICOMOS 1964). This document set the international standard for the conservation of cultural heritage as something essential to human understanding, in common international ownership but focused on evidence, authenticity, and the historic place as a document to be “read” and preserved through the application of science. The Charter identified that heritage places had to be recorded and understood in order to inform change and established a common, international conservation practice to be adopted by anyone who chose to use it.

The idea of CRM as something distinct from archaeological research began in the 1960s and 1970s and one of its outcomes was that the limitations of the Venice Charter were soon revealed. The focus of this change was in the United States and Australia.

In the 1960s the Civil Rights movement and the growing profile of Indigenous political issues in the United States was matched by a similar growth in Indigenous rights in Australasia. At this same time archaeology was emerging from the shadow of antiquarianism to be a science in its own right, and one of its main areas of activity was in the field of human origins, including the archaeological and ethnographic study of Indigenous peoples. This brought archaeologists into conflict with the developing rights and sense of identity of Indigenous groups. Coupled with the increasingly scientific approach of archaeological method (termed “processual archaeology” because it sought to identify and establish universally applicable behaviors and processes) was a new relationship with developers whose work was to impact on buried archaeological sites (chiefly through the construction of long distance pipe lines), but also on “living” Indigenous communities.

There were two areas of disagreement. First, Indigenous peoples rejected the processual approach because it was imposed without consultation, presented a limited idea of “culture” and took the management of their own cultural heritage away from their community. Second, successive heritage legislative acts in the United States required that “significant” sites (including Indigenous sites) could be added to the National

Register, but failed to provide any definition of what “significant/significance” might mean.

In Australia, it was discovered that the Venice Charter was not sensitive enough to allow the informed management of Indigenous sites because its perspective was essentially western and scientific and did not accept alternative ways of understanding culture. As a result, the “Burra Charter” was published in 1979 (Australia ICOMOS 2013). The Charter provided new definitions for old terms, such as “conservation” and “restoration” and established new concepts. The term “place” was introduced in preference to “site” or “building,” in order to make stakeholders think beyond the limitations of fabric, and crucially, “significance” and “value” were made key to heritage management. The “significance” of a “place” was understood as the sum of the “values” attached to it. These “values” were in four main groups: esthetic, scientific, historical, and social. The outcome of developments in the United States and Australia was that the management of the heritage “resource” became distinct from pure archaeology and a discipline in its own right.

CRM was adopted by practitioners in the United Kingdom where it was known as “rescue archaeology,” and as in the United States, a recognized process of assessment of sites was to develop, primarily based around desk-based assessment (literature and map surveys), geophysical survey, archaeological evaluation to test or “ground truth” the geophysics and then redesign of the proposed development or full excavation as ways of “mitigating” the impact of the proposal. In the United Kingdom as in the United States, CRM/CHM work is undertaken commercially, whereas in other parts of Europe, France for example, the state plays a greater role in the initial assessment of the proposed development site. Initially both CRM and “rescue archaeology” provoked considerable disagreement between the research and commercial arms of archaeology. The research side considered CRM to be “bad” archaeology because it was fast, unfocused, and commercially rather research driven, while the commercial side of archaeology considered contemporary archaeological research to be irrelevant, elitist, and slow to develop new archaeological techniques.

Issues

From being a discipline surrounded by controversy, CRM developed into a term that covered both professional practice and research/theory, but there is now recognition that the term CRM should be applied to the suite of professional practices only, while “critical heritage studies” is the related field of academic and research enquiry.

The recent changes in heritage thought have all moved towards promoting inclusiveness, participation, and cultural difference; putting people before fabric. The principal heritage management approach is termed “values-based,” because it adopts the main tenets of Burra, but it is not clear whether the potential of a “values-based” approach has been realized.

One outcome of the distinction between CRM/CHM and critical heritage studies is a widening gap between theory and practice. Because CRM/CHM is largely defined by a commercial imperative to consider only sites under development, there is a sense that “heritage” can be defined and quantified in the manner of a material “resource.” Heritage can be “used,” notably for tourism, and by extension the economy, but heritage theory considers heritage as limitless: each generation leaves its mark on the world but offers its own interpretation of what went before. Therefore the possible interpretations of a place, such as Stonehenge, Wiltshire, England, or Mesa Verde, Colorado, United States, continue expanding. In this sense archaeological sites, for example, never diminish in number because society makes “new” sites. This presents a considerable dilemma for CRM/CHM as policy and practice are not able to deliver current ideas because the existing legal and bureaucratic heritage process has not matched this new understanding.

In order to address concerns about lack of research focus CRM/CHM is increasingly supported by predictive modeling to identify where archaeological deposits are likely to be found and research frameworks that identify what is archaeologically significant about particular regions and subregions, thereby allowing focus on particular research questions. This change in practice has eased disagreement within the archaeological profession because the new understanding of

where sites might be has given greater context to research archaeology.

However, the manner in which this expertise is used remains under close academic scrutiny, particularly the manner in which practitioners define and attribute “significance” and “value” to places. CRM can be understood as an exercise in power relations, with the manager having all the power because legislation and policy have made them “responsible” for decision making. An alternative argument proposes that the resource manager should be seen as a “facilitator”—someone who draws out the many meanings and associations attached to places.

The continued analysis of the role of expertise has led some to question the effectiveness of the values-based approach to CRM. Some consider that the problem lies in the attitudes and role of the practitioners applying an “authorized heritage discourse” or AHD (Smith 2006). The AHD is that range of practice, guidance, and legislation that privileges cultural institutions, historic fabric, authenticity, age, attribution, and connoisseurship. Contrary to the AHD is an approach to heritage that acknowledges difference, cultural diversity, participation, and community, seeing heritage as “process” rather than “product.” “Heritage” is about the dialogue between past and present, not lists of nationally important places.

The way in which places are identified as heritage assets remains contentious. Many nation-states have their own designation system for identifying individual sites, places, or landscapes as nationally important, assuming that there is an agreed “national story.” An opposing view argues that the identification of individual sites is an expression of the AHD because it favors a limited range of values with many places or themes (gender, for example), not part of a “mainstream” narrative. One of the weaknesses of the individual site approach is that it creates a polarity between the “iconic” and the “everyday,” whereby values are skewed towards the iconic, ignoring those elements of place that make it human and personal. Allied to this is the idea that the “characterization” of a place offers a more plural approach to the understanding and management of the cultural heritage.

“Characterization” (Fairclough 1999) is essentially a mapping exercise looking at the historical

depth of a place and can be applied to any area, from an extensive landscape to an urban backland. Characterization considers that all places are valued by someone, are all cultural products and culturally perceived and therefore places should be considered “value neutral.” A second stage in characterization is wide consultation on the identification of the values attached to the elements that make up that place. The aim is that the management of places should balance the iconic and the everyday, and thus be more sustainable because it better reflects an often unspoken sense of place.

Although the condition of important international heritage sites provoked the creation of many conservation charters, the idea of World Heritage designation has generated concern. While the imbalance between the high numbers of World Heritage Sites in western Europe and the smaller numbers in other parts of the world is clearly recognized, of greater concern is the way in which World Heritage designation is taken as an assumption that tourism and income growth will follow. Analysis of this expectation and the complexity of the relationship between tourism, authenticity, and heritage management are major topics in critical heritage studies, because they raise the issue of the role of CRM expertise but also the narrow and frequently contradictory content of many conservation charters and guidelines.

Post-conflict reconstruction and post-disaster recovery are established themes in CRM, particularly since the collapse of the former Yugoslavia. Conflict has focused on community and ethnicity and made cultural heritage sites, both the iconic and everyday, legitimate military targets. However, CRM practitioners and academics are split between those who negotiate with and advise the military before and during conflict about cultural matters and those who believe that greater consideration and commitment should be given to postwar reconstruction. The core of this difference is the argument about heritage privileging the authenticity of fabric, the ancient, and the iconic as opposed to heritage being about people and the provision of support for the rebuilding of communities and giving those communities the opportunity to reconstruct their own heritage places in their own time.

Future directions

Questions about who heritage is “for” remain a crucial theme in CRM. In response practitioners recognize that CRM has to become more plural and participatory but has to counter the conservative nature of the conservation discipline and practice.

Public participation in heritage activities, and specifically archaeological excavation, could be seen as something socially, physically, and mentally beneficial for people rather than being something to extend knowledge. Many CRM professionals would find this incompatible with developer-led work where site safety and commercial sensitivity can be subject to legal agreement. One alternative is that nonprofessionals could become more involved in the management of undeveloped heritage places, applying the skills from their own experience under the guidance of CRM professionals. Experience in the United States has demonstrated the vitality of local and charitable groups and could be extended beyond the usual “address book” of those committed to heritage to embrace other communities.

Perhaps the two most interesting areas of research are those at opposing ends of the cultural heritage spectrum: the concept of “living heritage” and the potential of digital heritage. Much of the new work on “living heritage” is being directed by ICCROM (ICCROM 2016), but also includes new work promised in India. Also known as a “people-centered approach,” living heritage recognizes that people are connected to their heritage in complex ways and are best able to manage their own heritage. What this means in practice is less clear, but the potential for shifting the management of cultural heritage from practitioners to communities is considerable.

The possibilities of digital heritage have yet to be realized, as they embrace both practical applications and the fundamentals of CRM. Digital approaches to survey and recording offer speed, accuracy, and detail but also present the ability to “look” through material previously considered a hindrance to analysis. Dramatic changes can be anticipated in the presentation of cultural heritage, from the use of dedicated apps offering layers of interpretation to a greater ease of communication between heritage communities. If living heritage is an anticipated area of growth,

and the existing focus on community and values continues, digital applications offer the ability for peer and community groups to talk to and learn from each other—across the World—without recourse to “official” heritage practitioners. The possibility for a revolution in “bottom-up” heritage practice is real and could redefine professional practice and the role of expertise.

SEE ALSO: Aerial Photography; Airborne Laser Scanning and Lidar; Archaeological Fieldwork; Archaeology; Conservation; Disaster Archaeology; Heritage: Nonwestern Understandings; Heritage and Conflict Resolution; Heritage and Policy; Heritage and Value-Based Approach; Heritage Business and Marketing; Heritage Management; Value or Significance

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Designing and Co-Creating Heritage

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To communicate heritage, both tangible and intangible concepts must be not only interpreted but also expressed. Heritage is in this way performed, either directly or through representations and reconstructions—an act that solidifies the interpretation by giving it form and purpose. While heritage could be described as a set of values and understandings, not merely places, monuments, and artifacts (see Smith 2006), it is through the communication of heritage that meaning is collectively created. These expressed interpretations of artifacts or customs permeate society and thus play a pivotal role in a very active negotiation process, which serves to construct the meaning of heritage.

Co-creation shares a philosophical background with public archaeology and citizen participation, a mode of practice that encompasses outreach, education, and public interpretation and representation. However, public archaeology inherently leads to an asymmetrical power relation; the act of granting the public the limited power of participation both cements the scholar as instigator and gatekeeper and accentuates the public's lack of agency and resources. In contrast, co-creation describes a rhizomatic process, defined through a decentralized approach to heritage whereby the public is not directed by scholars but constitutes instead a creative force that shares the responsibilities of defining, caring for, and using heritage (Bollwerk, Connolly, and McDavid 2015).

As a process, co-creation can occur both at a community and at a societal level. At a community level, by engaging in dialogue with stakeholders, one can make a more diverse set of voices be heard. Stakeholders are not limited to those that are directly affected by a decision, but may also include those that perceive themselves

to have an emotional stake in a given place, artifact, or custom. By engaging a larger community of stakeholders, you pave the way for finding sustainable approaches to the management and development of heritage sites and memory institutions. This requires an organic approach to heritage, one that both empowers local industries and finds renewal in local initiative. To achieve this, heritage institutions should not stand outside society or dictate goals but should instead conduct an active dialogue with the public and develop a heightened sensibility to the unique situation of a community. By giving artifacts, monuments, or traditions a meaning for the local citizens, preservation can serve as an integrated part of the area's development. This sentiment is echoed in much of contemporary heritage practice, which has experienced a shift from a strong focus on material artifacts to a kind of preservation that also concerns itself with narratives and sociocultural contexts (Malpas 2008). However, this shift should not be seen as an abandonment of the material for the immaterial, since even immaterial culture is tied to materiality.

At a societal level, co-creation is not always expressed, or even thought of as such, as the processes that function to shape how heritage is used and expressed are not explicit. Instead, they are integrated into the visual design and communication of heritage. As a stepping stone toward communicating what heritage is, we make use of representations of artifacts and customs. In doing this we are bringing the public together with professors and students, museums and heritage institutions, and filmmakers, game makers, and other commercial initiatives. The actants of this assemblage are enrolled, either directly or indirectly, in the project of co-creating a shared representation of heritage. While far from always originating in academia, this is a formative process influenced by the techniques and symbols involved in the practical procedures of making a representation. The translations that these procedures bring about shape scholarly and popular visualizations alike. In fact one cannot separate popular representations from the world of science, since these representations create

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ideas about the past and cement those ideas in society, of which the scientific community is a part (Moser 1998). However, *despite* the fact that their impact is not confined to popular culture but shapes our understanding of heritage, the practical procedures and technologies involved in creating a representation have traditionally been treated by nonpractitioners as no more than a string of intermediaries—processes that carry an idea unchanged—and not as a network of actants far from neutral in their practice of co-creating what heritage is. However, as evidenced by those illustrators and co-creators who are making their voices heard both through academic publications and through contributions to major academic projects, an idea is shaped by the minutiae of the procedures that give it form.

As visual and multisensory representations of culture and heritage are often the tools of politics and ideologies and make up both identity and nationality (Ashworth, Graham, and Tunbridge 2007), these processes have a great impact on what heritage is perceived to be, whom it belongs to, and how it is represented. An understanding of the processes through which society designs and co-creates these representations of heritage is crucial, since such processes are often located at the junction between the researcher and the public. Positioned in such a way, the communicative conventions that these representations use form a large part of the public's grasp of heritage, while they limit the scholars' ability to express new results in an unmediated way. Indeed, heritage is what we *collectively* represent it to be, regardless of whether we have been invited or not. The way we interpret and represent our material artifacts—and how we give strength to those interpretations through narrations, visualizations, and sociocultural connections—shapes us.

Designing for transparency: giving heritage a meaning

For an archaeological visualization to be meaningful, it must take risks but still be firmly grounded in established ideas. It must operate according to culturally accepted rules, moving

a couple of inches beyond the borders of absolute fact, to fill in the blanks and create a whole (Ammerman 2006). Therefore a visualization is best viewed as a contextualization of an interpretation; lost materiality is replaced to create a whole and a scene is designed that communicates a social context. It is therefore not a visual representation of the original artifact but a visualization of one of many of its interpretations; and, as such, it is a creation as much as it is a reconstruction.

Scientific visualization, as a method of communication rather than personal notation, emerged in the fifteenth century. By being translated into drawings, findings made during expeditions could be brought back home, shared, and analyzed. In the nineteenth century the reconstruction drawing, which was used to place the findings in a context, gained ground as a technique through which to express interpretations and communicate relations (Moser 1998). This development was echoed in a steady increase in the practice of physical, material reconstruction of monuments and sites. During the twentieth century this practice gave rise to a number of charters drafted to offer counsel: the Athens Charter in 1931, the Venice Charter in 1964, the Florence Charter in 1981, the Dresden Declaration on Reconstruction in 1982, the Nara Document on Authenticity in 1994, and the Krakow Charter in 2000.

The charters argue that reconstructions raise concerns of historical validity, as they present persuasive and strong interpretations that are almost impossible to “unknown,” while at the same time turning the process of their construction opaque. This is no less true for digital reconstructions. Our heritage is increasingly experienced as a virtual heritage, a space consisting of representations. Three-dimensional scanning through photogrammetry and laser, virtual reality, augmented reality, photorealistic computer graphics, and interactive displays—all these are technologies that have started to shape the professional field. While advanced digital documentation and convincing visualizations used to be the mark of grand initiatives such as Rome Reborn, Catalhoyuk, and Vulci 3000, an increasing number of smaller projects have made 3D scanning and modelling part of their professional workflow. While being a synthesis of

information, a reconstruction, whether physical or digital, might also be described as a dialysis, as it separates the unwanted or unknown from the construction and reduces complex associations and interdependencies to an ordered whole.

However, the generally used definition of reconstruction as the representation of a lost physical reality ignores the active process of making a reconstruction—and this applies in equal measure to physical and to digital reconstructions. The *act of reconstructing*, closer to the definition of reconstruction as an action or process rather than as a thing that has been rebuilt, is a process through which it is possible to assemble stepping stones for other processes and actants, which leads to insights about sources, contexts, and places otherwise overlooked. As an active process, the reconstruction is both a product and a means of productivity, as the practice embodies a transformative dimension. Hence, while reconstruction is a visual representation practice, not only is it a crucial step in the dissemination of results; it also plays a central role in the scientific process of developing theories. However, to design the past is never a neutral undertaking, even when this is part of a scientific process: by default, certain *properties* are inscribed into the design itself. If the interpretation is allowed to become a part of the idea of the place, these properties are made durable by being translated into a seemingly material form.

As a bundle of both tangible and intangible parts, heritage is, in the words of Neil Silberman, an “ever-changing array of objects and symbols, a complex mosaic of artifacts, images, and customs, that demand our attention and demand that we give some meaning to them”; by contrast, the past is a lived reality that survives only in fragments and can only be experienced in retrospect (Silberman 2008, 82). Arguing that we can never re-create the past as it actually was, with a sense of uncompleted presentness and uncertain expectation, Silberman states that any visual representation of the past is from the outset bound to be lacking. This implies that there can be no definite representation or description, no design that encompasses the entirety of this construction, as there are always new perspectives, changing alliances, and neglected stakeholders

to take into account, and all of them challenge our grasp of the concept and make it grow. Likewise, as heritage is made up of intangible traditions and social history as much as of any physicality, the challenge lies in also recognizing the activities that *surround* a custom or an artifact.

The future of designing heritage

The strength of a visual representation is its ability to activate our senses; it translates a technical language into a framework to which all parties can relate. However, this strength may also be used to establish an interpretation as a final truth rather than as a hypothesis. Thus a representation can isolate us from the scientific work, since its strength lends it a preferential right of interpretation, even in cases where the scientific basis of the representation has been altered or deemed false, or when it simply conveys a more diverse set of interpretations. It becomes a conscious part of the public’s notion of a subject and forms its own basis in popular culture, ensuring a widespread effect. Hence a representation is not neutral but occupies the same mental space as the material remains, shaping both how we collectively perceive them and how we expect them to be presented to us. Brought on by the inseparable activities of heritage manufacturing and tradition consumption, this creates a reverse flow of cultural capital (Alsayyad 2008). In consequence, our understanding of heritage is shadowed by our representation of heritage—a representation whose stakeholders and co-creators are numerous and whose sociocultural ties need to be considered when new representations are created.

Archaeologists have always wrestled with issues of representation, but the emerging photorealistic digital visualizations of the last three decades have accentuated these issues; through their use of realistic-looking shadows, textures, and perspective, the photorealistic representations lend the interpretation all the attributes of a convincing physical materiality, which conveys a deceptive feeling of certainty (Shapiro and McDonald 1995). This demands greater responsibility from museums and scholars: they must

actively rethink the way they make use of images in their communication, since an unchallenged interpretation, incorporated into a large body of knowledge drawn upon by others, risks becoming a fact.

A reconstruction moves us simultaneously farther away from and closer to the primary sources upon which the reconstruction is built: *away* from the sources, as they are the result of an interpretation and, as such, are perceived by many scholars as losing the inherent validity of the material remains upon which they are based; yet *closer* to the sources, since a reconstruction can bring those to life and place them in a context where further theories and hypotheses can be explored.

All scientific work has a communicative aspect, where thought and theory are dressed in visual form. As reconstruction processes often lack transparency and may cement, for the recipient, interpretations that become hard to challenge later on, recent studies in the visual communication of digital reconstructions have explored different approaches to communicating the uncertainty, rather than the certainty, of an interpretation. The methods have ranged from systems for computing reliability through fuzzy logic to visual cues incorporated in the model itself, such as conflicting interpretations and color grading. The majority of these studies concern themselves with developing techniques through which the past can be represented as “correctly” as possible—the translation from findings to reconstruction is done in a neutral way, so as to not add any ungrounded interpretations, colored by social interaction or speculation. However, the design of visual representations should also be seen as both an interpretational and a creative practice.

New methods need to be developed that should offer inroads into questioning a visualization rather than making the audience accept it, and that could make the translation from idea to representation less of a finality and more of a dialogue—the past being presented as unsettled, as it is in the notes of the archaeologist and on the drawing board of the artist. As cultural properties derive from an artifact’s or a site’s contact with the functions of social interaction, past and present, the interpretation

of this contact must be performed and presented in a transparent manner, leaving a track of symbols and data that tell a more complete story.

SEE ALSO: Augmented Reality; Authenticity in VRM; Computer Applications in Archaeology; Critical Museology; Digital Photogrammetry; Heritage and Community Archaeology; Heritage Interpretation; Image-Based 3D Modeling; Photorealism and Digital Reconstruction; Re-Enactment and Engagement; Structure from Motion; Virtual Reality Modeling

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Experts and Stakeholders

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Introduction

For long an arena of “expert” engagement and control, heritage in the past few decades has seen a growing concern to draw in “stakeholders.” Experts are traditionally defined by their formal qualifications and knowledge, their expertise, and are very often paid professionals. Stakeholders are defined by their interests (whether place-based, community-centered, or thematic) and often by ownership in one sense or another. The relationship and difference between the two is a fraught area, and the drive for more engagement and participation in heritage is bringing underlying issues around experts and stakeholders to the foreground, which have major implications for both heritage practice and theory. This piece attempts to provide an international overview of theory and practice relating to experts and stakeholders in a heritage context, but is inevitably shaped by the author’s more in-depth knowledge of developments in the United Kingdom and published literature in English.

Heritage professionals in many parts of the world are increasingly concerned with encouraging members of the public to interact with heritage. Innovative approaches to interpreting (see *HERITAGE INTERPRETATION*) and presenting heritage to the public utilize ever more diverse ranges of media, including social media and immersive visualization technologies such as augmented reality (see *AUGMENTED REALITY*). Concurrently, developments in heritage management (see *HERITAGE MANAGEMENT*) call for professionals to encourage public participation in identifying and looking after heritage.

In the modern history of heritage, issues of experts and stakeholders have largely been

approached implicitly, but the questions of valid forms of knowledge about heritage that underpinned the discussions around the formation of the Nara Document on Authenticity in the 1990s (Larsen 1995) have become explicit in recent heritage charters. The Faro Convention (see *FARO CONVENTION*), for example, connects heritage and human rights (see *HERITAGE AND HUMAN RIGHTS*), giving rise to entire scholarly volumes on heritage expertise (Schofield 2014). Questions of expertise now sit at the center of the growing body of critical heritage studies, in which critical theory (see *CRITICAL THEORY*), and its foregrounding of politics, power, inequality, and exclusion are applied to heritage. Experts and stakeholders are therefore not simple distinctions between heritage professionals and the public, but contested value-laden terms that privilege selected interpretations of heritage, perpetuating existing power structures.

Defining experts and stakeholders

An expert is widely understood as an individual with superior knowledge or skill in a certain area; this superior skill or knowledge is referred to as expertise. Experts are often regarded as authorities on their subject and as such can hold considerable power. This power may be freely given in recognition of perceived expertise or imposed through legislation by authorities. A stakeholder is a person, group, or organization with a stake, understood as an interest or a claim to something. While experts are identified by virtue of their perceived expertise, stakeholders tend to be self-selecting and involve themselves in order to represent their interests. Stakeholders and their interests may or may not be recognized by decision makers, yet stakeholders are not employed or compelled, but choose to assert their interests.

With regard to heritage, the term “stakeholder” is almost exclusively used in the context of decision making in heritage management.

Nevertheless, many of the functions performed by cultural organizations operating on behalf of the public, such as public museums, are based on an understanding of members of the public as stakeholders. The perceived duty to present and display collections and sites accompanied by the results of expert research, highlights the sense that heritage does not belong to experts, as further demonstrated by the growing pressure to repatriate (see REPATRIATION) collections, especially in postcolonial contexts. New modes of engagement that invite audiences to interact with heritage more directly, coupled with developments in heritage ethics (see HERITAGE ETHICS) that emphasize respecting cultural diversity and legitimize nonwestern understandings of heritage (see HERITAGE: NONWESTERN UNDERSTANDINGS), are blurring established distinctions between experts and stakeholders.

Stepping beyond the complex issues of ownership, current heritage management literature and practice predominantly follow values-based approaches. These approaches are based on the premise that heritage is conserved and used because it is valued, and that decisions about heritage should be made on the basis of as comprehensive an understanding as possible of its values and significance (see VALUE OR SIGNIFICANCE). As a result, stakeholder consultation is increasingly advocated due to the recognition that expert knowledge alone is insufficient to inform multicriteria decision making. The expanding range of what is considered heritage, from the monumental and aesthetically pleasing to include complex landscapes (see HERITAGE AND LANDSCAPES), the vernacular, and the intangible (see MULTIVARIATE ANALYSIS), is also prompting the search for expertise beyond established expert circles. Despite this, traditional distinctions between experts and stakeholders, and the authority awarded to each, have remained largely unchanged in practice.

As heritage management continues to advocate plurality and multivocality, archaeologists are increasingly having to justify the primacy given to archaeological knowledge and expertise. Their perceived position of privilege is under pressure from critical heritage scholarship, which seeks a different balance between experts and stakeholders. While archaeologists engaging with these critiques have argued that archaeological

experts working as heritage managers should consider themselves heritage managers first and archaeologists second, in an effort to treat fairly the various values attributed to heritage (Emerick 2014), others regard archaeologists as powerful stakeholders who have coopted heritage and doubt the extent to which archaeologists can divorce themselves from their disciplinary training and preference (Waterton and Smith 2009).

Reasons for engagement and participation

Heritage experts and institutions are increasingly required to demonstrate their relevance and value to society. As a result, boosting engagement metrics, such as visitor numbers, and diversifying visitor demographics are becoming more important. A growing number of scholars are conducting research to demonstrate the wider social significance of heritage (see HERITAGE AND SOCIETY) to pressing concerns such as sustainability (see HERITAGE AND SUSTAINABILITY) and wellbeing, and to develop more accurate metrics that capture the full range of ways in which people engage with heritage. Heritage practice and research is thus increasingly underpinned by a belief that active participation and engagement in heritage activities provides social and individual benefits.

Despite the potential benefits to participants, stakeholder participation in heritage is also promoted to raise the quality and capacity of professional practice. The management of heritage sites and collections in line with the standards of best practice promoted by monitoring institutions and policy is often not possible without the active support of local communities and volunteers. Most archaeological sites are not guarded when professional work is not ongoing and rely on the involvement of stakeholders for protection. Many smaller museums and remote heritage sites are similarly reliant on the voluntary initiatives of stakeholders. Larger institutions often also depend on volunteers to complete large survey, digitization, and simple conservation (see CONSERVATION) projects that would not be viable with paid professional

capacity alone. When budgets are stretched thin, discussions of appropriate distinctions between professional labor and voluntary contributions inevitably arise, relating to issues of both ethics and expertise.

Concerns with heritage ethics (see *HERITAGE ETHICS*) and the implications of their application to values-based approaches (see *HERITAGE AND VALUE-BASED APPROACH*) have highlighted the contested nature of heritage and contributed pressure to democratize and decolonize heritage, especially in postcolonial contexts. As a result, in countries like the United States, Canada, Australia and New Zealand, decisions about how indigenous heritage is conserved, studied, and displayed are more often made in consultation with, or entirely by, Indigenous stakeholders, and the employment of Indigenous experts in cultural organizations is becoming more common. The conventions of the Council of Europe have spread these ideas of democratization and local knowledge to Europe by advocating for the legitimacy of stakeholders' memories (see *MEMORY*) and perspectives on place and identity as valid forms of knowledge about heritage. An example is the European Landscape Convention, which calls for the involvement of stakeholders in every stage of heritage identification and assessment to aid decision making and the formation of policies.

Alongside demonstrating the relevance of heritage to society and increasing the capacity and quality of professional work, public participation in heritage activities is advocated to facilitate connecting people to their heritage. By actively taking part in community archaeology (see *HERITAGE AND COMMUNITY ARCHAEOLOGY*) and community heritage (see *COMMUNITY HERITAGE*) projects, participants can gain a new appreciation for the heritage they have interacted with. Arguably, it is through interactions like these that new attachments to heritage can be formed, thereby increasing their significance within a values-based framework. It may be hypothesized, following hierarchies of learning developed in pedagogy, that deeper engagement or more involved participation will lead to greater attachment.

Methods for engagement and participation

The range of methods used by heritage professionals to provide more immersive and engaging heritage experiences is becoming broader. This enables heritage professionals to draw on and develop the expertise of stakeholders, simultaneously strengthening the attachments to heritage of existing stakeholders, and facilitating the formation of new stakeholder attachments. Traditionally behind the scenes processes, such as conservation in museums, are increasingly made visible through panels, temporary pop-up exhibits, purpose-built conservation studios that allow visitors to observe professionals at work, and participatory conservation projects where volunteers are allowed to perform conservation tasks with supervision. Similarly, some museums invite community curators, where stakeholders are given the opportunity to create displays. The most visible changes in traditional heritage environments are perhaps the continuing adaption of new technologies to provide more realistic and immersive experiences, as well as the use of the Internet to facilitate virtual visits from the comfort of one's home.

While volunteering has a long history in archaeology and heritage, the rise of Web 2.0 technologies and the social web have created new cultures of participation that extend to the heritage sector (Giaccardi 2012). These new technologies and cultures both facilitate and demand the development of new interactive modes of public engagement and participation. One of the most significant new approaches is crowdsourcing, which allows anyone on the Internet to become a digital volunteer. Crowdsourcing has the potential to allow institutions to perform tasks of a magnitude beyond their professional capacity, such as transcribing texts and tagging images or videos to create, and facilitate searches within, digital archives, but it is also increasingly employed as an engagement strategy (Ridge 2014). Crowdsourcing is not unproblematic however. There can be significant costs of developing and supporting crowdsourcing programs, and there are concerns relating to the ability of digital volunteers to perform expert tasks, with linked

issues of data validity. There can also be problematic ethics of crowdsourcing arising from its exploitative nature when commercialized.

As stakeholders continue to be recognized as valid sources of heritage knowledge, heritage professionals are beginning to utilize a wider range of ethnographic and qualitative research methodologies (see *ETHNOGRAPHY AND QUALITATIVE METHODS IN THE FIELD*) to access stakeholders' expertise. These methodologies are often utilized in conjunction with various forms of coproduction, such as countermapping (see *COUNTERMAPPING*), participatory GIS, and codesign (see *CULTURAL RESOURCES MANAGEMENT*), as well as research philosophies such as participatory action research, which deliberately further blur the traditional boundaries between experts and stakeholders by advocating research *with*, rather than *on*, participants. Crucially, these approaches do not only democratize research processes and produce new forms of research data, but they are also immersive engagement activities that can facilitate the development of skills and a sense of community ownership of heritage (Jones 2017), thereby providing an effective mechanism for stakeholder development and facilitating stakeholder agency in caring for heritage.

Critical perspectives on participation

As calls for participatory approaches to heritage practice have become more common, critical analysis is moving from the promotion of participation as a solution to an emphasis on participation itself. While power may be shared with stakeholders by inviting participation, it can also be retained through this invitation by controlling and managing the forms participation may take. A growing number of scholars are highlighting the mismatches between the promises and realities of participatory practice, especially those practices that employ supposedly democratizing digital technologies. It is becoming clear that while participatory approaches may have the potential to democratize heritage, participation can be as exploitative as it is emancipatory, and

may in some cases be equally as likely to exacerbate issues of diversity and representation as to solve them.

A critical perspective on participation originates with the identification of power. While participatory approaches invite stakeholder involvement, stakeholders may have limited agency over the nature of their involvement and their contributions may not carry much weight. Tokenistic consultations where participant perspectives are not regarded highly enough to influence professional preference can breed distrust of professionals and disillusionment with participatory projects. Reports on more involved participation in museums from countries like the United Kingdom and Canada, such as projects where communities are invited to participate in curatorial activities involving collections from their own culture, may also build resentment, where controlled access reminds participants of the injustice of forced separation from their heritage and any participation on their part is felt to legitimize the institutions responsible.

Issues of power are also highlighted in less charged volunteering contexts because ethical concerns raised by digital approaches, such as crowdsourcing, are becoming more common in the heritage sector. Participatory projects tend to be more expensive and less efficient, and it is unclear whether projects can unproblematically be motivated by both a desire for inclusion and the need to balance budgets, especially at a time of declining budgets. In light of the belief that heritage is a public good and that heritage services should be for public benefit, the concern that participatory projects may be exploiting volunteers is especially acute.

This issue is compounded by the growing prevalence of volunteer positions requiring qualifications and of unpaid internships and of the lack of paid graduate employment opportunities in the United States, United Kingdom, and much of western Europe. It raises fears that paid employment in the sector is becoming available only to those who can financially afford to gain experience and exposure through unpaid activity, which also exacerbates the existing lack of diversity within heritage professions. There may be a danger of a salary becoming the most obvious distinction between an expert and a stakeholder.

Critical scholarship is also highlighting that while participatory approaches claim to be democratizing and diversifying heritage, stakeholders are self-selecting, and populist democratization of heritage through open calls for participation may therefore reinforce existing power structures and produce less diverse narratives. This danger is especially acute in contexts where the boundaries between public engagement activities and participatory research projects are blurred; self-selection bias is insignificant in one but crucial in the other (Tourle 2017). Such blurring of boundaries between experts and stakeholders, and between different forms of engagement and participation, calls for the renegotiation of roles and responsibilities, as well as the knowledge and skills required of heritage professionals.

Future directions

Established expert and stakeholder roles, responsibilities, and perceptions of expertise are actively challenged in contexts where stakeholder groups initiate projects and bring professionals in as they see fit. In many of these projects, the nature of the stakeholder-expert relationship shifts; professionals become participants in, rather than the driving force behind, collaborative ventures. The distinctive dynamic of these projects arises from their origin among stakeholders, allowing volunteers to take leading roles and remain decision makers even when working alongside paid professionals. While researchers are noting that successful community-led projects can be powerful sources of social innovation, less attention has been paid to how such initiatives can be encouraged and supported without disturbing their dynamic. Similarly, while current research is beginning to address what makes public participation feasible and productive in different circumstances, less is known about how contexts initially less conducive to collaboration can become productive sites for participatory initiatives.

The changing dimensions of heritage engagement and participation are revealing the need for a wider range of forms of heritage expertise. While it is clear that heritage professionals are

increasingly called on to function as facilitators of collaborative ventures, this does not mean that traditional forms of expertise are no longer relevant or that professionals should set their technical expertise aside in order to adopt the role of an impartial facilitator. Arguably, the legitimization of a wider range of forms of expertise is required, not the devaluing of established experts. It should not, however, necessarily be assumed that established experts are the only potential source of these new forms of expertise, nor that they are the best candidates to fill the role of facilitator. It is through the negotiation of changing roles and responsibilities that the future nature of “experts,” “stakeholders,” and their relationships will be determined; these negotiations are ongoing in heritage scholarship and in heritage practice.

SEE ALSO: Authorized Heritage Discourse; Countermapping; Plurality and Multivocality; Public Archaeology

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Faro Convention

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Background and context

The Faro Convention (hereafter “Faro”) is the most recent of a number of Council of Europe (CoE) Conventions dealing with cultural heritage. Its tone and content reflect changes in perceptions about cultural heritage that have been inspired among heritage experts and political decision makers by key social concerns of the late twentieth century. These concerns include recurrent economic crises, globalization, the shift to an “information society” with more leisure time for many citizens, social tensions arising from demographic factors (including large-scale migration), and concerns over quality of life. Faro—its formal title being the Framework Convention on the Value of Cultural Heritage for Society—sees Europe’s shared cultural heritage as having the potential to offer ways of mediating or mitigating these forces.

The Council of Europe is an intergovernmental organization founded in 1947 which seeks to agree and raise common standards within Europe on matters concerning human rights, democracy, and the rule of law. Except for Belarus, all countries within Europe are members—47 in total. CoE is quite distinct from the European Union, though all 28 current EU members are also members of CoE.

Framing

Emphasizing the importance of the “common heritage of Europe”—self-evidently a cultural heritage—CoE wished to make a strong association with human rights and with the fundamental freedoms for which the CoE’s primary mission is to act as a guardian—in effect, a “right to heritage.”

Faro’s technical roots lie in major changes in heritage discourse and practice, largely in respect of the built heritage although intangible heritage is not excluded. The previous decades had seen a shift in focus from elite items of (built) heritage significance for their own sake (intrinsic value) and towards the sustainable management of a much wider range of heritage sites, objects, and traditional practices seen as assets to be used to benefit society at large (use value). The CoE’s aim in drafting Faro was to offer the approval of CoE, Europe’s senior intergovernmental deliberative forum on culture, for this new “democratic paradigm,” setting out guiding principles and offering guidance on how social value might legitimately be derived from heritage through sustainable use.

It was implicitly acknowledged that the traditional European model of state-funded protection and conservation of heritage was no longer sufficient, and required a new model characterized by “greater democracy, strengthened citizen participation, and better governance based on more open, reactive, and transparent institutions.” This shift towards a more open, democratic approach to defining and managing heritage reflected wider movements in practical politics away from state authoritarianism; it was accompanied by a preferred partnership model in which governments are no longer seen as the sole guardian of national heritages. Pragmatically, it recognized that (faced with an increasingly wide spectrum of social responsibilities) governments were neither best placed nor able to afford to intervene across the whole spectrum of heritage, the scope of which had expanded in the course of a century from a very few famous and ancient sites and buildings, to include much of the world in which Europe’s citizens live.

Drafting

The Convention was drafted during 2004 by a group of experts nominated by national culture ministries. The Group reported to CoE’s Steering

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Committee on Culture, Heritage and Landscape, and was supported by a small secretariat led by the present writer.

The expert group began with certain core concepts taken as given. The organizing principle would be cultural heritage as an asset to be valued for the practical use which society can derive from it, rather than as a burden to be borne for its asserted inherent value. Associating this with the idea of rights and the balancing responsibilities of individuals, communities, and civil society, was likewise a given, as was the idea of a participatory democratic approach.

From the beginning of drafting, the Convention was intended to be very different from the Council of Europe's earlier heritage treaties, the Granada and Valletta Conventions on the preservation of the architectural and the archeological heritage respectively. It shares themes however with the European Landscape Convention (the Florence Convention), including recognition of significance in the heritage of the everyday, an emphasis on participative action, and a multi-disciplinary approach. It was also deliberately different in its focus from the UNESCO World Heritage Convention (which deals with "elite" heritage sites only) although more in accord with UNESCO's Convention on Intangible Heritage.

CoE and many commentators have asserted that the important philosophical innovation of Faro was to place people and human values at the center of an enlarged and cross-disciplinary concept of cultural heritage. The phrase "people-centered" is widely used about Faro. Faro explicitly shifted heritage discourse towards human rights discourse, asserting that everyone has a right to engage with the cultural heritage of their choice, but also that such rights entail responsibilities. By coupling this with the concept of democratic participation in all heritage-related processes, it sought to ease the burden on governments by sharing responsibility for heritage protection across civil society.

The Convention itself

Writing international instruments is always a process of collaboration and compromise. For Faro

(Council of Europe 2005a), key compromises lay in defining terms, not least "cultural heritage." The Explanatory Report to the Convention explores these issues in some detail (Council of Europe 2005b).

Faro adopts a very broad definition of cultural heritage, which includes tangible and intangible aspects, as well as interactions. To date, this remains the broadest definition of cultural heritage in any major international instrument:

cultural heritage is a group of resources inherited from the past which people identify, independently of ownership, as a reflection and expression of their constantly evolving values, beliefs, knowledge and traditions. It includes all aspects of the environment resulting from the interaction between people and places through time

Core to Faro is a second definition, asserting that heritage acquires value through collective action by communities (rather than by expert-led valuation):

a heritage community consists of people who value specific aspects of cultural heritage which they wish, within the framework of public action, to sustain and transmit to future generations.

A specifically European dimension is added defining the common heritage of Europe as:

all forms of cultural heritage in Europe which together constitute a shared source of remembrance, understanding, identity, cohesion and creativity, and ... the ideals, principles and values, derived from the experience gained through progress and past conflicts, which foster the development of a peaceful and stable society, founded on respect for human rights, democracy and the rule of law.

It is important to note that this explicitly positions Europe's cultural heritage as a force for progress and simultaneously asserts that the vision of a peaceful and equitable society is itself part of Europe's heritage—although Faro does not claim any particular European uniqueness for this positive vision.

Having defined its terms, Faro sets out the concept of rights to heritage and their accompanying responsibilities: "everyone, alone or

collectively, has the right to benefit from the cultural heritage and to contribute towards its enrichment (and) the responsibility to respect the cultural heritage of others as much as their own heritage.” These rights may have limits, and Faro cautions that the “exercise of the right to cultural heritage may be subject only to those restrictions which are necessary in a democratic society for the protection of the public interest and the rights and freedoms of others.”

As a creation of an intergovernmental body, Faro is addressed to national governments. Those that ratify the Convention formally agree that the above rights exist. They also agree to formulate integrated strategies to facilitate the implementation of the provisions of this Convention and to take specific actions, such as to recognize the public interest associated with cultural heritage, to enhance the value of cultural heritage through identification, study, interpretation, protection, conservation, and presentation, and to have appropriate national legislative provisions for exercising the right to cultural heritage. They also agree to foster an economic and social climate which supports participation in cultural heritage, promote cultural heritage protection as a central factor in sustainable development, cultural diversity, and contemporary creativity.

Specific fields of policy making activity where Faro posits these general principles will bear fruit are in:

- benefiting from dialogue (how heritage is presented, how different interpretations and differing views are accommodated equitably, how better knowledge can promote mutual understanding, and how cultural heritage can play a role in all kinds of education and training);
- using heritage to add value to quality of life issues (economic, political, social, and cultural development), wider environmental management, and social cohesion;
- pursuing sustainable use and management; and
- exploiting the economic potential of heritage.

Faro requires signatory states to recognize the principle of shared responsibility for cultural heritage and public participation, by acting in four main areas:

1. Integrated, well-informed, and innovative cooperation—promoting approaches which respect voluntary initiatives and drawing into collective action public authorities, experts, owners, investors, businesses, nongovernmental organizations, and civil society more generally.
2. Access to and democratic participation in heritage—encouraging universal participation, reflection, and debate, taking into account the value attached by each heritage community to ‘their’ cultural heritage, recognizing the value of the voluntary sector as both partner and critic.
3. The inclusion of cultural heritage in education at all levels, in its own right, and as a fertile source for studies in other subjects—strengthening links between heritage education and vocational training, encouraging interdisciplinary research, and promoting all forms of knowledge exchange.
4. Harnessing the information society, by encouraging initiatives to promote content quality and linguistic and cultural diversity, and by seeking to improve access to information.

The Convention does not contain any provisions for enforcement—signatories must self-monitor, encouraged by NGOs and international associations. There is no “European Court of Heritage” to hold countries to account.

Progress since Faro was launched

The broad scope of the Convention, which led to it being entitled a *Framework* Convention, means that it is relatively easy for states to show that they are undertaking actions which are in the spirit of Faro. In many countries, the idea of “doing Faro” has become accepted shorthand for a participatory approach to heritage with shared responsibilities and mixed public and private resourcing.

Early ratifiers were predominantly countries whose independent existence had relatively recently been reestablished or redefined, principally in the former USSR and its associated bloc, and in the former Yugoslavia. In such

countries, cultural heritage as a contributory element of national identity tends to enjoy a high political priority. (The two early exceptions to this observation are Portugal and Norway, both of which were heavily involved in the drafting process at steering group and expert group level.) The Convention gained the necessary 10 state ratifications for it to come into effect in ratifying countries in 2011, but since then it has only slowly gathered additional signatories. As of early 2017, 17 of the CoE's 47 member states have ratified it, and a further five have reached the first stage of signing it (Council of Europe 2016). It may be doubted whether some countries will ever ratify it, especially amongst the larger countries of "old" Europe, not necessarily through lack of agreement with its principles, but through government claims that those principles are already widely accepted and acted upon.

CoE continues to promote the Convention, both as a source of inspiration and guidance and also as an instrument to be ratified. However (in the spirit, it could be argued, of the Convention's own participative ambition), the general idea of "Faro actions" has taken on a life of its own. In recent years CoE has focussed more on badging and endorsing a range of international activities as Faro-related than on encouraging additional ratifications.

SEE ALSO: Cultural Resources Management; Heritage and Conflict Resolution; Heritage and Economics; Heritage and Human Rights; Heritage and Policy; Heritage and Society; Heritage and Value-Based Approach; Memory; Plurality and Multivocality; Public Archaeology

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Heritage and Community Archaeology

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Heritage and community archaeology

Definition, principles, and scope

Community archaeology is archaeology by, for, about, and within contemporary communities, in which members of the public are involved in initiation, design, consultation, execution, management, interpretation, and presentation of investigations into their tangible heritage. Community archaeology lies at the intersection between public archaeology (see PUBLIC ARCHAEOLOGY) and community heritage (see COMMUNITY HERITAGE), but is focused specifically on the connection between communities and archaeological remains, whether held in museums, buried underground, ranged across landscapes, or surviving as upstanding buildings still in use.

The principle defining and underpinning community archaeology is that it is archaeological activity which simultaneously benefits archaeological remains, people, and communities. The justification for the first case is that *tangible heritage* will be better cared for by people whose understanding, empathy, and appreciation has been increased by engagement, while archaeological interpretation will benefit from new ideas from people from different backgrounds. In the second case, *people* will benefit by acquiring new knowledge, skills, aspirations, interests, social connections, and enhanced sense of connection with their place. Thirdly, *communities* will benefit as the process and outcomes of collective engagement with archaeological activities and discoveries contributes to place-making, strengthens social bonds, builds social capital, and boosts local economies.

The definition of community archaeology is not without difficulty, not least because “community” is itself a mutable construct (Isherwood 2012). It is often conceptualized spatially as a group of people connected by living in the same place, but such a definition may not suit people living outside the community but with a connection with it, or people who have little or no connection with people they live near. Furthermore, communities can define themselves by other criteria such as gender, economic status, occupation, hobbies, religion, ethnicity, sexuality, education, or health status. Complicating matters even further, while the term “community” can be inferred to represent a homogeneous group, any community will always contain internal differences, as people are multifaceted and will share different aspects of their identity with different groups of people. However, the essence of community archaeology is its focus on communities, however defined, and its terminological “fuzziness” in fact provides useful plasticity for a growing discipline to explore new directions.

The scope of community archaeology has been extensively debated, and while a broad consensus exists that it should aim to bring people and archaeological investigation together to the mutual benefit of both, it has proved more difficult to agree scope or remit more precisely. Faulkner and Moshenska, writing in *Public Archaeology* nearly a decade apart (in 2000 and 2008 respectively) both reflected the view that a project can only really be termed “community archaeology” if it is instigated and driven by its community. On the other hand, several contributors to the seminal 2002 *World Archaeology* issue devoted to community archaeology presented externally instigated projects in which communities have a secondary, mediated involvement (e.g., advising on designing a museum). Agreement has not even been reached as to whether precise definition is desirable: this is advocated by those who believe this to be essential if the discipline is to be taken seriously, and rejected by others who consider the circumstances that the subject encounters to be so diverse that attempts

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at definition will sooner or later prove either inadequate or counterproductive.

The morality of involving nonspecialists in archaeology at all has also been questioned. One argument holds that all archaeology should be “community” archaeology because the past is a collective asset and everyone has the right to connect with its physical remains. The countervailing view is that instrumentalizing archaeology to achieve any aim beyond simply protecting heritage assets or advancing knowledge of the past cannot be justified, as in setting other needs alongside those of the archaeological remains, as those of the latter may be jeopardized.

Difficulties can arise when there is potential for archaeology to have a negative impact on communities, which is possible in circumstances involving disputes over ownership of archaeological material (which may relate to sites, artifacts, or human remains), or when narratives derived from knowledge of the past are being corrupted to further political agendas or human rights abuses, or when livelihoods may be threatened by heritage protection measures. There are no simple answers to these questions because human societies are not simple, but ethical issues (see *HERITAGE ETHICS*) are always an important consideration when community archaeology projects are being developed.

Methods

Community archaeology is different from much other archaeology and from much other community work because it must respect both people *and* archaeology. Serving two masters is not easy, and assessing how to balance the degree of control exercised by archaeologists and non-archaeologists to ensure diverse aims are all met without damaging compromise requires careful planning, for which there is no simple formula: all sites and all participants differ in their needs and their capacity. There is consequently a wide degree of variation, both between schemes and within the same scheme, in how people participate: At one end of the spectrum volunteers may be restricted to simple routine tasks such as washing finds, at the other, volunteers may control every stage of project instigation, consultation, design, planning, execution, management, and reporting.

Whatever the situational context, community archaeology should be carried out to the highest archaeological standards, using methods and equipment for planning, fieldwork, recording, postexcavation and reporting most appropriate to meeting the archaeological aims (detailed in the “Field Methods” SAS entries), which should be detailed in the project design or written scheme of investigation. Similarly, community aims should be clearly identified and the methods used to achieve and evaluate these equally clearly elicited. Communities should be consulted at all stages, starting with project design. Members of the community should be able to participate as fully and autonomously as their knowledge, skills, experience, and abilities allow, while respecting the needs of others and of the archaeology under investigation. The whole team should work together respectfully and avoid an “us-and-them” division between professional archaeologists and volunteers. Everyone should have the chance to learn as much as they want to about the site and the project aims, and hear and give frequent updates about progress. Those in a supervisory or training role should be aware that volunteers will have knowledge and experience of value to the project, and endeavor to identify individual aspirations, needs, knowledge, skills, or interests so these can be met and deployed. Training and support should be appropriate and the pace of the project matched to the capacity of participants. Decision-making should be as democratic as possible commensurate with the need to meet identified aims, and should always be respectful of the opinions, feelings, and ideas of all who feel a connection with the project and its outcomes. The results of the investigations should always be shared with volunteers and with the host communities at all stages of the project in as many ways as possible to ensure wide access while evaluation of the outcomes should include community aims. The benefits of the project should be shared as widely and equitably as possible.

Conducted according to those principles, community archaeology schemes can educate, inform, inspire, and upskill participants while also advancing knowledge and understanding about the past and its impact on the present, enfranchizing volunteers and communities, developing notions of place and identity, and contributing to place making by advancing

and democratizing “insider” knowledge about the past.

Changes over time in the topic and its treatment

Community archaeology is a global phenomenon which has followed different but interconnected developmental trajectories in different countries. Before the twentieth century there were no professional archaeologists so all archaeology was in effect community archaeology, but involved very narrowly defined communities. In the United Kingdom “antiquarian” activity was largely restricted to gentry and aristocratic circles until the mid-nineteenth century when expansion of education and transportation encouraged the foundation of county archaeological societies whose members ran museums and carried out excavations. These communities, defined by a shared interest in archaeology, were numerically small and dominated by relatively affluent, educated males mainly interested in high-status sites. Participation broadened a little socially as local groups appeared in towns and rural parishes, accelerating in the postwar years as higher education and adult education expanded and the Council for British Archaeology (CBA) and the British Association for Local History (BALH) were founded in the 1940s. Although membership remained mostly middle-class, groups enthusiastically took the initiative in finding local sites to excavate and new academic interest in deserted medieval villages prompted some to explore past communities spatially more closely connected to the places they themselves inhabited.

In the 1960s and 1970s, growing interest in heritage and environmentalism encouraged and enabled county planning offices and many museums in the United Kingdom to appoint professional archaeologists to record, monitor, and protect archaeological sites, collaterally nurturing community engagement. Job creation schemes such as the Manpower Services Commission (1973–87) gave hundreds of unemployed people work on community archaeology projects such as Raunds (Northamptonshire) and La Grava (Bedfordshire), many commissioned specifically for this purpose. Museum archaeologists such as

Peter Liddle in Leicester published early technical guidelines for community archaeology and founded networked groups which still thrive more than 30 years later (<http://leicsfieldworkers.co.uk/>). The decades after World War II were the first golden age of community archaeology in the United Kingdom.

However, by the late 1970s the tide began to turn. UK government programmes were cut during recession and in many community groups the laborious process of postexcavation analysis began to outstrip the capabilities (or even lifespans) of some of their instigators. New techniques made excavation increasingly informative but also more specialized, complex, time-consuming, and costly, and by the end of the 1980s many professional archaeologists employed to protect the archaeological resource prioritized its preservation and saw excavation as a last resort, only to be carried out by trained and experienced professional archaeologists if sites were threatened by development. Opportunities and support for community groups to take part in excavation became more restricted, and their dwindling number became detached from professional archaeologists.

Communities elsewhere across the world were also frequently disconnected from their local archaeology. In countries such as Australia, Africa, the Middle East, and the United States, archaeological investigation had been introduced in the eighteenth or nineteenth centuries by colonial incomers with no connection to local communities: antiquarians interested in collecting “native” artifacts or unearthing classical or biblical remains typically either ignored local people or used them as laborers. With a few notable exceptions the situation improved little until the 1970s when, in response to wider political campaigns for recognition of the rights of indigenous people, across the world projects in America, Africa, and Australia began to offer different ways of working with local and descendent communities (Ucko 1983). In the United States at Ozette, Richard Daugherty excavated throughout the 1970s at the invitation of the local Makah tribal council, who retained a significant degree of control throughout the project, ensuring finds and records were retained locally in a purpose-built cultural centre. In Africa, Peter Ucko in the 1980s brought to

global attention politically motivated racist misinterpretations of indigenous archaeology produced in white-ruled Zimbabwe. In Australia, Shelley Greer and Susan McIntyre-Tamwoy developed a community-based approach to archaeological fieldwork in northern Cape York using ethnographic interviews and community workshops.

In the United Kingdom, Mick Aston's "Shapwick Project" exemplified participative community archaeology "about, by and within" local communities: hundreds of local people took part in archaeological investigations into the long-term development of this rural English village, with the results regularly reported to wider publics in diverse accessible local venues including village halls and local fetes. The project significantly advanced subject knowledge in final publications which included a 400-page "popular" volume formally dedicated to "the people of Shapwick, past, present, and future."

At the turn of the millennium, while frustration with the lingering gulf between members of the public and "official" archaeology remained (Faulkner 2000), progress was evident in the arrival of a new academic journal, *Public Archaeology*, soon followed by a special issue of *World Archaeology* dedicated to community archaeology in 2002. The latter highlighted the role of community archaeology in empowering local communities, and methodologies for achieving this were developed and refined, stressing the need for archaeologists to cede at least some of the decision-making to local or indigenous communities. In the United Kingdom from 2002, the Heritage Lottery Fund (HLF) did exactly that, explicitly directing increasing proportions of the hundreds of millions it granted each year to projects proposed by communities and involving public participation (Maeer 2017). By 2010, Suzie Thomas' survey for the Council for British Archaeology showed that around 215,000 individuals belonged to more than 2,030 active archaeology groups in the United Kingdom, 41 percent of which were involved in excavation with others carrying out fieldwalking, photographic recording, attending talks, and heritage lobbying (Thomas 2010).

In the second decade of the twenty-first century, many of these community archaeology groups have become increasingly autonomous, helped by initiatives such as the joint HLF and the

Arts and Humanities Research Council *All Our Stories* scheme which in 2012–13 put community groups firmly in control of proposing project ideas and controlling budgets, which allowed them to buy in expertise and training to suit their aims and needs. In eastern England this enabled thousands of people from scores of communities to take part in community-instigated projects including local excavations which engaged communities while also advancing understanding of long-term change (Lewis 2016). The UK Localism Act (2011) introduced "Community Rights," which encouraged communities to draft "Neighbourhood Plans" to shape local development and nominate buildings or land (in private or public ownership), including heritage, as Assets of Community Value, which could not then be sold without the community being given exclusive first rights to bid for purchase. The gulf between community archaeology and the "professional" archaeological sector narrowed, in the United Kingdom at least, as loss of income from developer-funded archaeology in the post-2008 financial recession encouraged many professional archaeological organizations to offer their services to independently funded community archaeology projects.

At universities, engagement with local communities has been encouraged by burgeoning interest in coproduced research (devised and run jointly between universities and communities). Since 2014, papers in each issue of the new *Journal of Community Archaeology and Heritage* show community archaeology as routinely participative as well as consultative and instrumentalized.

The present

Over decades or, in some places, over centuries, the relationship between archaeology and communities has evolved, at different rates and not always happily, from one characterized by oblivious elitism and exploitation successively to embrace consultation, participation and instrumentalization and to nurture coproduction and community autonomy. The core aims and objectives of community archaeology are now well-established, its outcomes are increasingly widely valued, and its underpinning principles embedded in legislation and professional practice

in countries as far apart as Australia, Canada, and the United Kingdom as well as by the World Archaeological Congress and ICOMOS, while there are a growing number of forums in which experience, practices, and principles of community archaeology can be shared, sustaining a usefully informed and largely collegiate, outward-looking dynamism.

The future

In the future, community archaeology will need to develop its capacity to evidence its achievements and to refine understanding of the relationships between communities and archaeological remains and the mechanisms and processes which can articulate these for the common good (Gould 2016). There is scope to improve its ability to work in a truly interdisciplinary manner to achieve wider social aims, improving synergies with disciplines such as community work, social work, education, public health, and psychogeography to advance understanding of how communities work (Isherwood 2012). Community archaeology will need to increase its reach and diversity so that its benefits can be more widely felt by people, communities, and archaeology. It will need to respond to new digital technologies, which will not only diversify the ways in which wider publics can engage with archaeological investigation (already evident in crowdfunding, crowdsourcing, live streaming, gaming, and augmented reality) but also enable communities to form and act in new ways, including in how they relate to archaeology. Most importantly, community archaeology will need to respond to a changing world: the comments of Shelley Greer and colleagues writing in *World Archaeology* 15 years ago that “Archaeologists may expect increasing contestation between themselves as ‘experts,’ the community, and regulators until such time as new methods and practice are introduced which provide for adequate community involvement” (Greer et al. 2002, 283) are resonant in 2017 as populism and nationalism rejecting so-called “elites” and “experts” are loudly heard in political discourse.

SEE ALSO: Community Heritage; Heritage Ethics; Public Archaeology

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Heritage and Conflict Resolution

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Heritage is about inherited identity, a means of building and reaffirming cohesion within a group, and distinguishing it from others. Therefore, heritage is sensitive in conflict between groups; sometimes destroyed, sometimes looted, sometimes given or taken back. The Arch of Titus in Rome depicts the victors carrying away booty from the destruction of the temple in Jerusalem in 70 AD, an act that still resonates in today's regional conflict.

When heritage is returned after conflict it may happen as part of a unilateral process reasserting identity and rights, or as part of a reconciliation, recognizing the sovereign identity of "the other." Historically destruction is better documented than the use of heritage for conflict resolution. Cicero denounced the illegal appropriation of cultural property in 70 BC, but the restitution of war booty is first documented with the return to Italy by British troops of heritage from Louvre that had been looted by the Napoleonic armies. Third party postwar restitution remained the prevailing form also after World War II. Examples of voluntary direct restitution between former adversaries remain rare, but reconstruction of built heritage as a means of conflict resolution between former adversaries is sometimes seen.

Direct restitution has however emerged as a manifestation of postcolonial understanding of indigenous people's rights. Former colonizers (whether foreign states, e.g., United Kingdom or France, or states imposed by European colonizers, e.g., United States or Australia) have returned museum objects to the heirs of people whose rights were violated.

Types of conflict-impact on heritage

When heritage is destroyed during armed conflict it happens for a variety of reasons, working in combinations or alone:

Collateral damage is probably the most common cause for destruction. Fortifications for example were built in positions of strategic importance, and are therefore still likely to attract military activity. Today's warfare is increasingly urban, and historic urban structures will be affected. Buildings such as bridges, belfries, and minarets may become military targets.

Damage inflicted for economic reasons plays a major role. Historic structures may become seriously degraded when adapted for shelter by civilian refugees. Illegal and legal art markets can encourage looting, especially of archaeological sites. This trade already exists in peacetime, but tends to accelerate when war reduces other income for civilians and warriors.

Deliberate targeted destruction is designed to demoralize a population defined as enemy. By destroying people's historic imprint on a landscape, their historic right to presence is denied. Often it comes with ethnic cleansing, as seen during the 1990s Yugoslav wars, or in the aftermath of the 1915 Ottoman expulsion of Armenians from Anatolia.

Unintended destruction of built heritage may also follow ethnic cleansing. When buildings and monuments are abandoned by their original inhabitants, they may suffer from lack of use and maintenance or from an unsympathetic use.

Damage by disrespect arising from a perception of colonized cultures as inferior, for example the removal of antiquities or human remains to museums and universities in the colonizers' country, deprives people of their heritage, even if the aim was ostensibly to "preserve."

Using heritage for conflict resolution

The possibilities for using heritage as a means of conflict resolution depends on why and how

heritage in each instance was affected by the conflict, and on the conflict's current state: settled (i.e., the parties have accepted its outcome, such as World War II), or frozen (i.e., the *casus belli* or disagreements remain unresolved (e.g., Cyprus, Kashmir, Nagorno-Karabakh)). Whether the populations involved still live where they used to before the conflict is equally important, and so is the question of whether the former adversaries live as neighbours or are segregated. Finally, it matters under which political, social, and economic conditions the parties live.

The major challenge of working with heritage as a resource for conflict resolution is the plethora of parameters affecting the outcome. This is not a field where archaeological, architectural, or art historian expertise suffices. Depending on circumstances, different constellations of expertise from social sciences, psychology, economics, police, and military will be necessary for the success of a heritage project aiming at contributing to conflict resolution. Still more important is to involve the different fractions of the population.

Case studies

The following provides an overview with examples drawn from a variety of contexts of heritage used for conflict resolution.

Postcolonial conflict resolution deals with restoration of respect for the dignity of the colonized party. Europeans and North Americans legitimized their subduing of other people and their lands as a "*mission civilisatrice*." Colonization not only took place in the form of overseas expansion, but also as continental expansion into lands inhabited by indigenous populations that was not necessarily declared as colonization but presented as "natural expansion." This is how the United States (itself originally an overseas colony) expanded towards the west and south, Russia expanded east, north, and south, and Sweden and Norway northwards into Sami lands.

The study of colonized people and their cultures was part of colonialism's ideological project, and often involved moving artifacts and human remains to museums and research institutions for exhibition and study. In 1915 researchers from the University of Oslo removed 94 Sami

skeletons from a local burial ground in Neiden, northern Norway and brought them to Oslo (Svestad 2013) to study a population that under the prevailing race-theoretical paradigm was a primitive proto-Mongolian race. When the question of the ethics of holding on to the remains was eventually raised, a commission including representatives of the Sami authorities and the local community was established to seek a solution. The result was a reburial in 2011 near the original graveyard, but it was a decision accompanied by doubts and questions. The ritual for reburial was difficult to decide upon, since some skeletons were pre-Christian and others not. There were some voices in the Sami community in favour of keeping the collection as a unique material for research. The whole revisiting of the 1915 removal of the skeletons from the burial ground reopened old wounds in the local community. This is just one out of many global examples where indigenous people have reclaimed remains of their ancestors.

Post-Civil War conflict resolution is increasingly relevant with civil wars becoming a dominant form of armed conflict at this stage of history. When a fragile peace was finally established in Bosnia, the international community engaged heavily in projects to bring back damaged heritage. Often the focus was on the symbolic value of the monuments. The single most famous example is the restoration of the Mostar Bridge, feeding both on the phenomenological metaphor of "the bridge" and its well-published destruction by Croat forces. The project drew considerable global media attention and support from UNESCO, the World Bank and the EU. Yet it is debatable how well suited it is as a model for future projects.

Basically, there are three main lessons to learn from the Mostar project: First, physically the bridge did not span a gap between the Bosniak and the Croat part of Mostar. Both sides of the river were inhabited by Bosniaks. The bridge was a sixteenth-century Ottoman construction and by the Croats seen as "not our heritage." Secondly, the internationally funded project failed to meet this challenge by engaging the local Croat community as stakeholders. Finally, despite high publicity the reconstructed bridge together with other internationally funded restoration works was insufficient to help Mostar develop

an independent tourism that could generate significant income and employment for both communities. Mostar remained a subordinate destination for one-day tourists, generating little economic activity. It is easier to point to such shortcomings than to offer an obvious recipe for success, but there should have been stronger focus on working with the local communities of (former) enemies as key stakeholders, and on integrating the projects in a socioeconomic program that would benefit all sides.

Some of the Bosnian heritage projects are not contributions to reconciliation, rather they have created enhanced landmarks of entrenchment. Such is the case when churches are rebuilt with higher belfries than the originals, or when mosques are rebuilt not in the original Bosnian style, but in Wahhabi style reflecting the source of project funding instead of heritage.

Civil wars can be difficult to separate from wars between states. Cyprus is an example of a civil war that immediately accelerated into a Greek–Turkish war. After the war, the international community engaged in heritage projects on both sides of the Green Line, dividing Greek and Turkish controlled parts of the island. The projects in Nicosia/Lefkosia are focused on both Turkish plus Muslim and Greek plus Christian heritage conveying recognition of a duality of Cypriot heritage on both sides of the Green Line. But that duality may itself become over emphasized at the cost of the hybridity between Greek, Turkish, and Levantine culture that is an important constituent of Cypriot heritage.

Post-World War II reconciliation and conflict resolution with heritage as an asset has been exemplified with considerable variety. We can distinguish projects focused on reclaiming heritage destroyed during war, from projects focused on heritage generated by war (i.e., battlefields and memorials). In the first instance, we can think of the seventeenth century Frauenkirche in Dresden, which was one of many historic buildings (Neutzner, Hermann, and Zwicker 2006) destroyed during the British and American air raids on February 13, 1945. This example is particularly illuminating because the building and the story of its destruction has served different ideological narratives (see Rothenburg 2015, 98–127).

Firstly, in the last days of the Nazi regime it was used as an example of allied barbarism that

destroyed the historic city. Secondly for the GDR regime it served as an example of the inherent barbarism of the “Anglo-American air-gangsters” now the main enemy of the Soviet-bloc. During the cold war the ruin was left as a monument to the enemy’s cruelty. After unification of the two Germanys, a huge international fundraising operation was launched to rebuild the church as a monument for peace and reconciliation. Dresden was twinned with Coventry, a British city that had suffered an equally devastating German air raid. Today church and political leaders from both cities commemorate together on the anniversaries of the two bombings. On top of the dome of Frauenkirche sits a golden cross crafted by a goldsmith from Coventry whose father took part in the bombing of Dresden. It could have been a perfect example of heritage used for reconciliation. But the history of the bombing remains disputed. Every year accompanying the official commemorations there are violent confrontations involving both right and left. There are also minor manifestations to disrupt the official program and challenge the official narrative. Still the main emphasis of the commemoration is on dignity and reconciliation and on reaching out towards victims of present conflicts. The Frauenkirche had been destroyed in a way that can be perceived as an act of targeted heritage destruction and its reconstruction as an international initiative, and its consistent use as a focus for joint commemoration with Coventry, is an example of a heritage project that has contributed significantly to reconcile populations once seeing each other as enemies.

Post-World War I. The first industrialized armed conflict saw sufferings and destructions on a hitherto unseen scale. The war created heritage in the form of titanic destructive transformations of large landscapes. Places such as Verdun were transformed physically and mentally, in such a radical way that they reached a point of no return to what they had been before. The landscapes around Verdun became hallowed ground, a monument for the sacrifice of the French nation in an epic fight with Germany (see Amat, Filippucci, and Savouret 2015, 46–68). Six villages that had been at the centre of battle were never rebuilt, but left as monuments and declared, “*Mort pour la France.*” As time and generations passed, a

transformed nature matured and the memories of those who lived through the war gradually gave way to the reception of those who came after. Some of the most obvious scars of war became less manifestly present, and through several stages the perception of World War I evolved from one of national sacrifice to that of a seminal disaster in a common European history. When at the seventieth commemoration in 1984 French President Mitterrand and German Chancellor Kohl stood hand in hand at the monument and cemetery of Douaumont (Verdun), the understanding of common tragedy, suffering, and reconciliation was definitively given preeminence and included in a meta-narrative of European unity.

In recent decades, archaeology has made significant contributions to highlight the conditions of the soldiers who fought (Desfossés, Jaques, and Prilaux 2008; Schnizler and Landolt 2013). This helps penetrate the anonymity created by the massive scale of the armies and of the industrialized killing. Today at Verdun French and German flags fly together alongside that of the European Union.

Post-Holocaust

In another field of industrialized mass killing archaeology has proved its potential. The archaeology of the KZ-camps of the Third Reich has developed a strong contribution to the understanding of the extent of the camps and their individual roles in the system of mass extermination of people defined as enemies by Nazi Germany (Colls 2012). This exposure of physical evidence is crucial for the common ability to remember, to learn, and to avoid future conflicts escalating into similar crimes.

Characteristic of these examples of heritage from the two world wars is that both Dresden and Verdun have lately been explicitly used in an open discourse to reconcile former enemies. The acts of war have been openly dealt with in the process. There are other examples where conflict resolution and reconciliation is more difficult. In the relationships between Japan and the countries it attacked before and during World War II heritage has not been used in the same way. The many Koreans who died in Hiroshima were not part of the official motivation for Hiroshima's

World Heritage Status. The repeated visits by Japanese government members to the Yasukuni Shrine in Tokyo that commemorates persons who had served the nation and some of whom are also listed as war criminals by other countries is an example of heritage (the shrine) used in ways that prolong the themes of conflict.

Turkey–Armenia

Heritage projects serving reconciliation need not deal openly with difficult issues related to conflict. After 2010, there has been increasing cooperation between Turkish and Armenian experts in the preservation of Armenian heritage on the territory of the Turkish republic. The focus has been on strictly antiquarian issues related to surveying and ranking of the monuments and their need for preservation. Often, they are of very high historic value but heavily damaged, sometimes by nature sometimes by human action, with or without intention. The fact that the Turkish authorities in 2012 nominated the historic city of Ani for UNESCO World Heritage status (granted 2016) has been an important gesture towards the Armenians. Even though the two parties seem unable to establish a common understanding of what happened to the Ottoman–Armenian population in 1915, they can now use heritage as a platform for cooperation and dialogue.

Conclusion

The development of projects using heritage for reconciliation should understand the factors behind the conflict in the first instance, and what role identity and cultural heritage have in the conflict. Social and economic factors such as unemployment and poverty may be the most important drivers behind a conflict, whereas identity as expressed through religion, language, and heritage may offer markers of difference, instrumentalized as symbolic rallying points for the parties to escalate the conflict. Heritage projects aiming at conflict resolution should address both the socioeconomic and the symbolic aspect. This can be done by using heritage to generate jobs and income (Lindblom and Paludan-Müller 2012) and through an emphasis

on heritage as an expression of exchange of impulses from various cultures. In areas of mixed cultures where communities have been pitched against each other, it is crucial to emphasize hybridity and common heritage.

SEE ALSO: Heritage and Economics; Heritage and Human Rights; Heritage and Nationalism; Heritage and Politics; Heritage Business and Marketing

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Heritage and Ecomuseums

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The most recent definition of an ecomuseum is “a community-based museum or heritage project that supports sustainable development” (Davis 2011, 85). At the core of ecomuseums lie the key elements of community, place, and characteristics that include holism, territoriality, democracy, and an inclusive definition of heritage (nature, culture, intangibles). Ecomuseums are often defined by a geographical territory, but one that might cut across political boundaries, or be defined by a shared past, or by a patois or a tradition.

No matter where they are located in the world, all ecomuseums are deeply embedded within a locality and reflect and celebrate local identity and local distinctiveness. Community dialogue, debate, and participation are central to ecomuseum principles; these processes deliver more meaningful interpretations of how local heritage—including archaeological sites, the built environment, local traditions, and the natural environment—reflects aspects of place. It includes the histories of inhabitants and all the sources of evidence, tangible and intangible, that have been socially identified and constructed to be considered of lasting value. However, ecomuseum practices are not simply dedicated to conserving aspects of heritage, but also provide a system of norms and values that contribute to shape habitus and a locality where “sense of place” is manifest. Ecomuseum establishment enables communities to identify, conserve, interpret, and manage their natural and cultural heritage resources for sustainable development—communities recognize and conserve heritage for themselves, which represents a “bottom-up” approach which runs counter to the “authorized heritage discourse” (Smith 2006).

The idea of the ecomuseum is perhaps best demonstrated by an example. The Ceumannan

Ecomuseum is based in Staffin, the most northerly peninsula of the Isle of Skye, Scotland, arguably one of the most spectacular landscapes in Britain. The area is one of rugged mountain scenery hiding secluded grassy plateaus and small freshwater lakes, and has a dramatic coastline with stacks, pinnacles, and hidden coves. The coastal rocks are predominantly Jurassic age with Tertiary exposures, rich in fossils and supporting colonies of breeding seabirds and populations of rare plants. In 2004, the Staffin Community Trust was awarded almost £200,000 from the United Kingdom's Heritage Lottery Fund and European sources to develop an ecomuseum, the first in Scotland, and indeed the first in the United Kingdom at that time. The Trust, which includes representatives from local voluntary groups and organizations, took responsibility for development, with aims to stimulate economic growth through tourism, encourage social activities in the community, improve local services, and strengthen sense of place. Ecomuseum supporters have undertaken a range of ambitious projects. Aware of the wide range of natural and cultural assets that attract geologists, naturalists, and walkers, projects have been largely devoted to historical and environmental themes.

The Staffin Ecomuseum promotes 13 sites of interest to visitors and local people by encouraging them to discover the area on waymarked trails. These include Quiraing, the rock face that towers above Staffin; dinosaur footprints on the shore at An Corran; Flodigarry's Viking connections; scattered crofts at Brodaig; and the Staffin Museum at Ellishadder which houses excellent local geological collections. This low-key ecomuseum could be a model for many others to follow; it is closely linked to community identity, local history, memory, sense of place, and economic development.

The roots of the ecomuseum movement can be traced back to France in the 1960s, although the word “*écomusée*” only came into use in 1971 after being coined by museologist Hugues de Varine. Since then the concept of the ecomuseum has evolved from its initial focus on rural material culture and lifeways, becoming adopted as a

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means of achieving community-heritage projects within a defined geographical territory in order to benefit local communities and conserve heritage assets. Early ecomuseum definitions included that of Rivard (1988, 125) who provided a useful comparison between the traditional museum (building + collections + experts + public) and the ecomuseum (territory + heritage + memory + population), whereas Varine suggested that the label ecomuseum was nothing more than “an opportunity to run with new ideas, to be imaginative, to initiate new ways of working, even to be audacious” (de Varine 1992, quoted in Davis 2011, 83). Today, the concept of the ecomuseum is regarded as an active expression of the school of thought known as “New Museology” that emerged between the 1960s and 1970s; the original new museology focused on how museums might assist disadvantaged communities, becoming a social actor in a process of societal, cultural, and environmental transformation. While traditional museums have frequently favoured high culture, ecomuseums encouraged an appreciation of the significance of “commonplace heritage” as local people began to recognize, value, and interpret their own cultural and environmental resources. This approach chimes nicely with the philosophies of the United Kingdom-based organization Common Ground, which has done much to generate enthusiasm for “everyday” heritage.

More than 400 ecomuseums exist around the world, the majority in Europe. They demonstrate huge variety in terms of the extent of their geographical area, from the Kalyna Ecomuseum in Canada which covers several thousand square kilometers of Alberta (and includes a National Park as well as other wilderness areas) to the Hemp Ecomuseum in Carmagnola, Italy, an old rope works which is housed in a small outdoor space of a few square meters. The ecomuseum observatory database (www.irespiemonte.it/ecomusei/) records that 98 percent of ecomuseums are located in rural areas and emphasize the link with local history, archaeology, local landscapes, natural resources, biotopes, and agricultural practices.

Ecomuseums also differ in terms of their management and governance practices. Although ecomuseum philosophy suggests they should be initiated and managed by local communities, a significant number are privately managed

or have been created by public bodies such as National Park authorities or local government to create networks of local heritage attractions, many of which are volunteer-led. However, the majority of sites are managed by, or work closely with “Associations,” local interest groups of activists. Ecomuseums jointly managed by local associations and public authorities are also common. For example, the Ecomuseo del Castillo de Ainsa (Spain) is a rural ecomuseum managed by the Fundació por la Conservación del Quebrantahuesos, a national nongovernmental organization which has the objective of assisting the recovery of populations of the Bearded vulture (*Gypaetus barbatus*) in the Spanish mountains. The Babia Góra Ecomuseum in Malopolskie, Poland is an ecomuseum founded in 2003 and managed by a local association; it promotes a network of places of natural and cultural heritage interest. The Ecomusée Daviaud in the Vendée region of France is an active member of the eco-Vendée network managed jointly by the local communes of Ocean-Marais de Monts.

Theoretical discourse about ecomuseums frequently makes connections to concepts of place and “sense of place.” Feelings about place may be derived from the natural environment, but are more often made up of a cocktail of natural and cultural features, and include the communities that live there. Our perceptions of places affect us, and places modify our behavior. In terms of heritage, this is important when we try to understand its significance and the role that heritage might actually play in the construction of “sense of place.”

All people have their own place, or perhaps several places, where they feel they “belong.” Terms such as “belonging,” “sense of place,” “identity,” and “community” are all related to ideas about place. Other terms seeking to capture the relationship between people and place, including sense of experience, topophilia, place identity, place attachment, insidedness, local sentiment, and community sentiment, have been coined by academics from several disciplines, including psychology, geography, anthropology, ecology, sociology, and cultural and heritage studies. These views, which stress attachment to place, have led Davis (2011) to claim that a major objective of ecomuseums is to strengthen sense of place and to promote a positive and

dynamic relationship between communities and their environment. Unsurprisingly, the “alternative heritage discourse” regards local people as the guardians of their own place and their own heritage, and the key actors in preserving the distinctive characteristics of their place (Smith 2006). This emphasis on local heritage and territorial identity—and the role of inhabitants in the regeneration of places—can be regarded as a reaction to globalization and cultural homogenization. Community engagement is increasingly recognized in UNESCO Conventions, and in the European Landscape Convention guidelines, which emphasize the interrelationships between local people and their environment.

Casey (1996) argues that place must be experienced: “there is no knowing or sensing a place except by being in that place, and to be in a place is to be in a position to perceive it;” in other words, place becomes a conceptualization of identity. Hence, ecomuseums are important in

that they provide a means of place exploration and help to express a deep conviction to preserve and deepen their own sense of place. They have the potential to provide local people with a process for rescuing fragments of heritage, a building, a redundant factory, a habitat, a form of intangible heritage, or a way of life from loss or destruction. To aid place exploration, many ecomuseums have developed a “fragmented site” approach, encouraging the visitor to explore the local area by visiting several local heritage sites. This split-site approach is arguably the most common feature of ecomuseums worldwide; the ecomuseum is not limited to a building or even a museum site, but encompasses everything within the region it refers to as its “territory.” Here, key sites have special meaning and are integrated into the museum. Heritage is recognized as being more than just archaeological or historic sites and material culture: it also encompasses memories, beliefs, folklore, legends, dance, music, and



Figure 1 The necklace model for the ecomuseum.

Source: Used by permission of Bloomsbury Publishing plc, from Davis, Peter. 2011. *Ecomuseums: A Sense of Place*, 2nd ed. London and New York: Continuum.

song. At the extreme, the ecomuseum includes everything within its territory. Intangible local skills, behavior patterns, social structure, and traditions are as much a part of the ecomuseum as the tangible evidence of landscapes, archaeological remains, geology, wildlife, buildings, and objects, and people and their domestic animals. Ecomuseums can be conceptualized as the string of a necklace holding together these heritage assets (Figure 1) (Davis 2011).

In conclusion, it is important to recognize that ecomuseums, local heritage, and places are deeply connected; the one characteristic that appears to be common to all ecomuseums is their pride in the place that they represent, promoting both its natural heritage and tangible and intangible cultural assets. Ecomuseums enable local people to gain social and cultural capital through their involvement; most importantly, they encourage dialogue between local people and visitors, so promoting a better understanding of the special nature of a locality, its history, sense of place, and local identity. Since the 2000s, ecomuseums have undergone a significant change in emphasis as their paradigm has been adopted to encourage economic growth, tourism, and gains in cultural capital. The new role for ecomuseums identified in China, to aid indigenous rural communities and safeguard their cultural assets (Davis 2011, 236), suggests that ecomuseums will continue to evolve to meet a wide variety of local needs as the concept becomes better known.

SEE ALSO: Archaeology and Tourism; Archaeoseismology; Biogeography; Community Heritage; Critical Museology; Environment and

Landscape; Heritage and Economics; Heritage and Human Rights; Heritage and Nationalism; Heritage and Politics; Heritage and Society; Heritage and Sustainability; Heritage Business and Marketing; Heritage Interpretation; Heritage Management; Planning and Tourism

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Heritage and Economics

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Economics has been defined as the study of the allocation of scarce resources, where scarce means that the available amount is low relative to demand. Heritage, for instance, ancient inner cities or older housing with characteristic architecture, is appreciated by many, but in limited supply. How can the economic returns of this historic capital—the benefits it provides to visitors and inhabitants—be measured? Should investments in heritage be stimulated through the use of public money?

An important part of economics is the “theory of value.” Its purpose is the determination of the value to society of commodities and their efficient use. The market is the primary mechanism for the allocation of resources, but economists have also been interested in the valuation of goods that are not traded. The nonstandard properties of such goods make them more challenging to study. Heritage is a case in point. The remnants of the past that are still with us can hamper further development, but can also occupy a useful place in the present. Many European towns have inner cities dating to the middle ages, whose streets are obviously less fitted to automobiles and public transport. The restructuring of Paris from the 1850s directed by Hausmann destroyed substantial amounts of heritage but made the city more suitable for modern times. On the other hand, cities like Venice that preserved their built environment are generally considered to be an important part of society and to be highly valued.

Hausman’s Paris is today appreciated by many, but he encountered fierce opposition in his time. It was not clear to all that the loss of an earlier version of the city was outweighed by the creation of the new one perhaps better suited to modern needs. Economists tend to think of projects like this in terms of what they call cost–benefit analysis. They make a list of all the losses and gains

for society associated with a project and try to make them comparable by expressing them in monetary terms. If adding all entries results in a positive number, it is concluded that carrying out the project is in the interest of society.

The focus of this discussion is on applying this methodology to the built heritage, and more specifically on measuring benefits, because while the costs of maintaining heritage are often all too clear, the benefits are usually more difficult to measure. At this point economics, and more specifically the theory of value, can make a contribution.

Heritage often takes the form of an amenity that is available to many without any obligation to pay for it. Any visitor of Amsterdam can enjoy the canal belt without being charged. The absence of a price for this type of heritage complicates determination of its value. Economists have accepted the challenge and developed techniques to measure the value of such local public goods and in what follows, the application of some of them to value heritage will be discussed.

From a welfare economic point of view the valuation techniques just discussed are interpreted as revealing the social value of heritage, that is, the value that society attaches to this amenity. If one accepts the assumptions underlying this view—the most important probably being that it’s the *use* of heritage made by current and future generations that matters—the results of the valuation exercises have normative value.

Heritage indicators

Economists are not experts in heritage. They use quantitative methods to do their research, which often implies that they use crude indicators for heritage content like a 0–1 variable indicating the monument status of a property or the size of a preservation area expressed in square kilometers. This does not indicate a lack of respect for the many relevant aspects of heritage that cannot all be measured in a quantitative way, but should be interpreted as an attempt to make the best use of

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limited quantitative indicators. It is nevertheless the case that by using them, economic analysis runs the risk of missing relevant and interesting aspects of heritage valuation. Future work may address some of these shortcomings (Ahlfeldt and Holman 2015).

Property prices

Hedonic price analysis is probably the most important technique for valuing local public goods. It assumes that characteristics of a house jointly determine its value for the user. In a competitive market all aspects of this value will be reflected in the price. Potential buyers searching for a house compare their characteristics and prices, and look for the best choice. Think about two houses that are identical in all aspects, except one, for instance, heritage content. The difference in price between the two is the value consumers attach to this aspect. Even if such ideal pairs do not occur in practice, statistical techniques allow an estimation of the impact of one characteristic on the price. This technique provides information about the value of heritage embodied in the house itself. It can also be applied to assess the impact of heritage resources located in the vicinity.

Using monument status as an indicator of the heritage embodied in the house, it has been found that in Dutch cities heritage is worth 5–10 percent of the value of the house. Monuments in the vicinity have a much smaller impact that is only significant when there are many, as happens in ancient inner cities. Research has concentrated on houses, but there is some evidence that the same phenomenon is present for particular types of office activity such as notaries or some consultants, who are willing to pay a premium for being able to use historic buildings.

Monument status is a rough heritage indicator, covering a lot of heterogeneity. Its main advantage is that it is based on expert judgment. A potential disadvantage is that monument status often also implies that ownership rights are limited by obligations to preserve the monument, and in principle such restrictions may reduce the property's price. The premium for monuments measured by hedonic analysis should thus be viewed as the net effect of the average value that

the heritage resource embodied in the property has for its users and the effect of the binding restrictions implied by the monument status. More detailed investigations of the value attached to a heritage resource could be obtained by using more specific indicators. In practice they appear hard to find and the year (or period) of construction is often the only alternative for monument status. In the Netherlands houses constructed in the first half of the twentieth century are in strong demand. Hedonic price studies show that such houses do not depreciate but rather increase in value over time, in sharp contrast with houses constructed after World War II. Part of this increase may be caused by improvements introduced in such housing, but note that such investments are themselves triggered by the attractiveness of this vintage housing.

Urban areas

The research findings discussed in the previous section refer mainly to private benefits for the occupier of a house or office. The external effects of heritage, that is, the value attached to it by those who don't have to pay for it, are more interesting for social cost–benefit analysis. Many Europeans appreciate the amenities of older inner cities by regularly visiting them for shopping, dining, or entertainment while living in suburbs with modern housing. The inner cities are an amenity that is valued by the inhabitants of the whole urban or metropolitan area. One may attempt to measure its importance by studying the location choices of households. A recent literature in economics has emphasized that, next to jobs, consumer amenities also play a non-negligible role in making a city an attractive place. For instance, the contrast between central Paris and downtown Detroit probably has to do with the overwhelming amount of heritage present in the former city, including that created by Hausmann's transformations. This attracts richer households whose spending stimulates the presence of restaurants, bars, specialty shops, theatres, and so forth that further enhance the attractiveness of the central area. The vibrant city center is an amenity for inhabitants of the whole agglomeration and increases its attractiveness as a

place to live. In this way consumer amenities can act as an important complement to employment.

The study of household location assumes that households make a deliberate choice between urban areas based on their characteristics. The methodology is thus similar to that of hedonic analysis, although the focus of interest is now on the location and not on the price. However, if house prices adjust to the forces of demand and supply, they are explained as well by the location choice model. One can compute the willingness-to-pay of households for the various urban amenities. Empirical estimates indicate that this can amount to several thousands of euros (van Duijn and Rouwendal 2013). To interpret this number properly, it should be noted that it does not refer to the old buildings in the protected inner city *per se*, but to the ancient inner city as it functions in the current urban setting. That is, it is not just the medieval houses but also shops, restaurants, and bars that drive the results. The models do not allow the separation of the “bricks and mortar” of ancient buildings from their current uses. However, these endogenous amenities are themselves, at least in part, only there because of a heritage resource. Even after correcting for this possible overshooting, location studies suggest an enormous social value of urban heritage.

A particular advantage of studies of location choice, in comparison to hedonic analysis, is that they allow investigation of possible difference in the willingness to pay for heritage between household types. A general finding is that willingness to pay for heritage among higher educated people exceeds that of others (and only partly because of higher incomes). This is significant in view of the consensus among urban economists that a skilled labor force is of utmost importance for urban growth and prosperity. There is also some evidence that the attractiveness of urban heritage is stronger for those working in “creative” sectors, and weaker for those with “technical” jobs, like IT.

To conclude, a word of warning. The results just discussed should not be interpreted as denying that jobs have priority over amenities for making cities attractive. Household location studies show that heritage is valued less in areas without a strong concentration of jobs.

Tourism

The benefits of heritage extend even to people who do not live in the urban area in which they are located. Tourist spending is important for the local economies of many historic cities and is often its main industry. However, it would not be correct to regard all this expenditure as expressing the value attached to heritage. The reason is that most of these tourists would have spent their money anyway, although probably at different places. Put differently, heritage influences the distribution of expenditure but these are not welfare effects. To properly measure welfare effects, one should compare the actual situation in which heritage is present with an alternative one in which it is absent. Consumers would probably spend the same amount of money, but their utility would be lower. The total expenditure associated with their trips does not measure the willingness to pay for the specific destination.

The economist Harold Hotelling developed a methodology for measuring the willingness to pay for goods like national parks in the United States that laid the foundation for the modern approach for measuring the benefits of trip destinations. He reasoned that the travel costs associated with visiting a national park could be included as part of willingness to pay calculations. The “travel cost method,” as it became known, has later been generalized to situations in which consumers can choose from many destinations. Estimated models of trip choice behavior allow computation of the willingness to pay for additional heritage—for instance, more monuments or a larger preserved historic area. Such models have recently been estimated for vacations, shopping and dining trips, and trips to rural destinations with walking or cycling as the main travel purpose. In all cases heritage turned out to be a significant element of destination choice behavior.

Effects of investing in heritage

All the results referred to above concern the value of existing heritage. For policy makers the relevant question is often whether it is economically worthwhile to invest in heritage through

maintenance or restoration. Economists attempt to answer this question from a welfare economic point of view. Subsidies to maintenance and restoration are justified if the social benefits exceed the cost. If all the benefits of such activities accrue to the owner of the property, there is no reason for spending public money on them. However, if there are benefits to others who do not pay for it—the inhabitants of the neighborhood in which the property is located being potentially the most relevant group—the owner does not have the proper incentive to take the right decision. If they have to bear the full cost while gaining only part of the benefits, they will be inclined to underinvest in maintenance and restoration. A subsidy equal to the benefits that will be experienced by the others is then justified, but to determine the value of this subsidy these external benefits have to be estimated.

Recent research has employed hedonic price analysis to address this issue. The idea is that investment in heritage—subsidized restorations of national monuments—has an impact on the prices of nearby houses. The area becomes more attractive as a residential location, hence demand increases and (with limits on the supply of new housing) therefore house prices rise. The higher prices reflect the value attached to the improvements in the national monument and can therefore be interpreted as the willingness to pay for it by the residents. As an example, spending 1 million euros on restoring a national monument in the Netherlands leads to an increase in house prices in the vicinity of approximately 3 percent (Koster and Rouwendal 2017). Although this may not appear to be a large number, the relevant area is large enough to make the total external benefits exceed the cost.

Another recent study investigated the redevelopment of abandoned manufacturing sites in the Netherlands that were kept in large part in their original state. It was found that the negative impact on the surrounding neighborhood that was present before redevelopment disappeared, and could be replaced by a positive external effect. This happens mainly in urban areas, however, and is hardly measurable outside the larger cities. It is not entirely clear what causes this difference, but perhaps rural open landscapes provide a good substitute for living in the vicinity of

manufacturing heritage (van Duijn, Rouwendal, and Boersema 2016).

Heritage in the urban landscape

Heritage is often part of urban areas and codevelops with the cities in which it is located. Although the literature on which the previous sections were based takes the designation of monuments and preservation areas as exogenous, this is in reality almost certainly not the case. Designation is only useful if there is a commitment from residents and local authorities, and the experts that decide on designation often take this into account. The presence of well-educated residents with higher incomes helps to stimulate interest in the preservation of characteristic buildings and to support joint efforts to preserve the characteristics of a neighborhood. Designation as a preservation area strengthens this process by ensuring continuation of that practice and thus offers some protection to the required investments (Ahlfeldt et al. 2017).

Protected status implies restrictions on future (re)development which bite more if the option to redevelop in an unrestricted way is more binding. Consistent with this observation, it has been found that protected areas on Manhattan, the most dynamic part of New York, did not show higher prices than surrounding areas, whereas properties in protected areas in other parts of the city were significantly more expensive (Been et al. 2016).

Recent developments in the literature paint a more vivid picture of the role of heritage and the way we deal with it in urban and regional economics. The economic importance of heritage is established beyond reasonable doubt. Current and future research may be expected to clarify further the processes that lead some buildings to end in obsolescence and demolition, while others are—often also after a troublesome period—rejuvenated and successfully integrated into a significantly changed environment.

SEE ALSO: Archaeology and Tourism; Conservation; Cultural Resources Management; Heritage and Policy; Heritage and Value-Based Approach; Heritage Business and Marketing;

Heritage Management; Heritage Planning and Design

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Heritage and Human Rights

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The universal nature of human rights was set out as *for everyone without distinction* in the Universal Declaration of Human Rights (UDHR), which was adopted by the United Nations General Assembly on December 10, 1948. However, the definition of human rights, as set out in the UDHR and subsequently in international law, does not define the role of culture or of cultural rights. UNESCO (1970) debated whether human rights included cultural rights—such as the right to participate in cultural life, the place of culture and tradition, group rights versus individual rights—and argued that these should be given attention. Over the past few decades, a number of meetings, conventions, and publications have debated the issue of cultural rights (Silverman and Ruggles 2007; Langfield, Logan, and Craith 2010; Meskell 2010; Ekern et al. 2014). However, these debates also concluded that the right to culture is limited at the point where it infringes on another human right. We can thus argue that cultural rights cannot simply be placed on a par with human rights, not least because “some cultural rights as locally practiced might be argued to abrogate human rights” (Silverman 2014, 7875). Similarly, “human rights and cultural heritage are not self-contained; they may overlap and in doing so may conflict with each other” (Silverman and Ruggles 2007, 6). This clearly sets up a tension as to whether culture, or specifically heritage, is a fundamental human right.

Unsurprisingly, there is no clear definition of cultural rights or agreement on their status, in part because cultural values are always contextual not universal. Heritage is contextual because it lies in the interplay between values—not simply local and nonlocal values, but also values among and between individuals and groups. These may be in conflict and are seldom shared—certainly

not on a universal scale. Nevertheless, there are certain strengths to considering cultural rights. As Appadurai states:

the global commitment to cultural heritage can be given a new relevance by using the perspective of cultural aspiration. This has a double value since cultural heritage can include problematic memories, divisive values and anti-democratic practices. By insisting on a constant dialogue between the capacity to aspire and the capacity to remember, we can provide a system of checks and balances, so that aspirations do not become unrealistic and memories do not become exclusive or xenophobic. (Appadurai 2002, 11)

Human rights such as dignity and justice surely need to be seen as driving forces behind decision making with regard to heritage and its management. The issue is about power in decision making—not about cultural rights per se. Many argue that the language of international human rights has shifted toward a unified language of global justice and governance. “Rights talk thus operates to leverage power in arenas of political debate and discourse ... using the language of rights can underscore the importance of the interests at stake, and the need for special kinds of justification attached to those interests” (Meskell 2010, 853). It is this rhetoric that may prove most useful.

A workshop in Oslo in 2011 entitled “Our Common Dignity: Towards Rights-Based World Heritage Management” (papers were published in the *International Journal of Heritage Studies*, and then as Ekern et al. 2014) advocated a rights-based approach to heritage management as a means of centering such debates. Subsequently this concept has been expanded upon in a joint IUCN, ICOMOS and ICCROM report from a workshop entitled “Building Capacity to Support Rights-Based Approaches in the World Heritage Convention: Learning From Practice” and held in Oslo in April 2014 (see IUCN, ICOMOS, and ICCROM 2014). This development may offer an important way forward in conceptualizing an ethical standpoint for heritage management.

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Values: the intersection of cultural diversity, heritage, and human rights

It is evident to anyone who works in the field that there are problematic disjunctures between conserving and managing cultural heritage, recognizing diverse values and stakeholders, making heritage intellectually accessible, maintaining and promoting cultural diversity, and developing participatory processes, when all of this is set against a broader and fundamental backdrop of supporting and promulgating human rights.

Values-based management has received considerable attention in recent years, providing a theoretical conceptualization of the importance of recognizing, articulating, and taking account of differing views of the same realities, of different ideas of importance to heritage—places, landscapes, and materialities—and their associative values, and of different perceptions of the importance of heritage for the present and the future.

UNESCO, in its cultural conventions, has emphasized the understanding of and tolerance for other cultures and has founded concepts that are based on universal values and mutual respect across cultural boundaries. But what are universal values? How does this notion accord with local values and with the spatially specific and contested nature of heritage?

The definition of an outstanding universal value (OUV), as expressed in the most recent version of UNESCO's Operational Guidelines at the time of this writing—the 2016 one—is as follows: "Outstanding Universal Value means cultural and/or natural significance which is so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity" (para 49). However,

a major challenge with World Heritage concerns a risk of gradual disassociation of OUV attributes from the values of local communities, social practices and lives. First, local values, cultural continuity and practices have often been dismissed by international conservation priorities. Second, an often held misperception is that effective protection of OUV requires excluding or displacing local values and their holders. (IUCN, ICOMOS, and ICCROM 2014, 7)

Indeed, there would appear to be a basic and fundamental contradiction between UNESCO's emphasis on diversity and the concept of universal value.

As Helaine Silverman (2014, 7875) asked: "Can and should cultural rights and human rights be universalized as encompassed by UNESCO's various declarations—beyond the idealistic notion of all of humankind being enriched by the enjoyment of everyone's cultural heritage?" When identifying "universal values," UNESCO is effectively putting forward a simplified version of historical value or significance, as perceived by a subset of heritage professionals. Key values of economic development, identity (local or national), political recognition, and so on are not overtly part of the selection criteria: but we are well aware that these are among the key values that drive state parties to nominate properties, and are very often part of the crucial political context for the World Heritage Committee's decision-making process. These values also lie at the core of many of the conflicts between the state and local stakeholders, and often at the core of development issues that directly impact upon the human rights of local communities. These conflicts create tensions between the values of international communities, states, and local communities; between professionals, bureaucrats, administrators, experts, and users; between local knowledge and professional expertise.

Heritage is often seen as vital for the articulation of cultural identity. So where does that leave the local, the state, and the international community when it comes to reconciling different values? Lynn Meskell (among others) has argued that, "in an ideal world, 'heritage rights' would include rights of self-determination and expression, rights of access and management, rights of veto, and rights to accrued benefits whether social, economic, spiritual, and so on" (Meskell 2010, 842). These ideas are echoed in many works that advocate a "living heritage" approach.

However, a distinction might be drawn between contemporary communities engaged the use or conceptualization of heritage spaces or places, or in material culture (such as indigenous communities), and contemporary communities that inhabit the space previously occupied by past societies with whom they may or may not feel any relationship and in whom they may or may

not be interested. Indeed, most contemporary societies have witnessed historical or ongoing migration, which profoundly changes the way people perceive their societies, and also impacts their engagement with the past societies that lived in the place they now inhabit. In all these cases heritage may be more or less important in framing an understanding and appreciation of “place” for local people; but it also recognizes that its own value will be different for different people and groups. Heritage also recognizes that this may well extend beyond local inhabitants. Tourism, heritage, and cultural organizations have all used the concept of “unique” to promote cultural tourism, to define a competitive advantage over other destinations. But this “uniqueness” is also used to define a place, a community, or even a state, which can lead to conflict over values and identities and can bring cultural values directly into conflict with human rights.

Recent debates, keen to be seen to be moving away ethically from top-down solutions and from the dominance of “expert opinion,” risk creating similarly simplistic and naive positions, which favor the rights of local inhabitants over those of all others. Expertise is not easily acquired in any field, and to disregard experts in heritage management, conservation, archaeology, education, tourism, and so on would be as disastrous as ignoring local values. The idea of a veto, or predetermined rights of accrual, on the basis of proximity to a heritage site, needs to be treated with caution. It also follows that the concept that “heritage rights, by their very nature, are likely to be locally and culturally understood” (Meskell 2010, 842–3) is an oversimplification: many values will be best understood at this level, but not all, and the notion of wider value judgments, of examining from different perspectives, must not be underrated or sidelined.

There is, however, no doubt that heritage and, specifically, heritage sites have been used as powerful tools in both supporting and attacking the human rights of communities throughout the world. The display and the interpretation of heritage sites have been used to assert minority identity—as a tool for resistance and the expression of difference—and, conversely, to oversimplify cultural differences and to assert alternative nationhoods. The latter, in particular, have challenged political autonomies and undermined

the values of communities, destroying the “very fabric of society” (Silverman and Ruggles 2007).

Therefore it is important that many archaeologists and heritage professionals increasingly see themselves as conduits and facilitators rather than arbiters and seek to enable all stakeholders and affected communities to engage in the decision-making process and in its outcomes. It recognizes the different rights of stakeholders to be part of the decision-making process, not simply part of a consultative paradigm. This move from values-based management to rights-based management may herald a more ethically centered discipline, which recognizes the role that heritage management and heritage rights have to play in supporting broader human rights.

Conclusion

We need to be very careful that cultural rights are not simply equated with more fundamental human rights, as set out in the UDHR. Article 2 of the 2005 UNESCO Convention on the Protection and Promotion of the Diversity of Cultural Expressions stated (visit http://portal.unesco.org/en/ev.php-URL_ID=31038&URL_DO=DO_TOPIC&URL_SECTION=201.html):

Cultural diversity can be protected and promoted only if human rights and fundamental freedoms, such as freedom of expression, information and communication, as well as the ability of individuals to choose cultural expressions, are guaranteed. No one may invoke the provisions of this Convention in order to infringe human rights and fundamental freedoms as enshrined in the Universal Declaration of Human Rights or guaranteed by international law, or to limit the scope thereof.

Nevertheless, we might argue that rights-based approaches are an extension of values-based approaches, in that they reflect the idea that some values are rights, not just interests or concerns. This could be a very useful construct, designed to promote critical debate on the values of specific heritage and the uses that it is put to. It could also ensure that the consequences of the decision making and actions of heritage professionals are considered within a broader framework than that of “what is best for the heritage.” Heritage is about

people and human values. Archaeologists and heritage experts are involved in the political ramifications of how heritage is used and perceived in the present. Exploring past societies, managing their physical remains, and interpreting these materials are twenty-first-century activities rooted in contemporary society and its issues: identity, political power, access to economic resources, development strategies, and so on can all be affected by what archaeologists say about the past. What is clear is that both the study of heritage and its preservation and management have to be set within wider concerns for human dignity and human justice. Practitioners do not need to be “deeply concerned about social, economic, and political inequities worldwide” (Silverman 2014, 7874) in order to recognize that, in contemporary society, their research and actions have consequences.

Understanding and empathy with plurality and cultural diversity, in recognition of the 2001 UNESCO Declaration on Cultural Diversity, must be critical to our thinking and teaching. As Andrew Sneddon (2014, 1895) comments, “the process of bringing the poor from the periphery to (or closer to) the center of heritage management has been a complex one.” The UN placed “lifting the world out of poverty” at the core of all its activities, and this is reiterated in its Millennium Development Goals. The UN’s cultural arm, UNESCO, stated that “key areas where culture can play a decisive role in the forthcoming international development agenda have been identified: poverty eradication, quality education, sustainable environmental management, sustainable cities, and social cohesion and inclusion” (see <http://en.unesco.org/themes/culture-sustainable-development>).

On the other hand, whether owing to external pressures, regional variation, or existing heritage practices, many world heritage tools and approaches remain grounded in expert knowledge and top-down planning. There is a continuous and urgent need to engage more actively with the implementation of rights-based approaches in the heritage sector (IUCN, ICOMOS, and ICCROM 2014, 8).

We need to see aspirational action. The Oslo workshop in 2014 suggested some useful policies, advocating that “governance following rights-based approaches is inclusionary and

shared, based on equality, adequate representation and mutual understanding” (IUCN, ICOMOS, and ICCROM 2014, 10). However, these policies continue to mix and confuse rights with democracy and rights with “being local” and fail to acknowledge that some cultural rights will be in conflict with other stakeholders’ rights or beliefs, or indeed even with their basic human rights.

SEE ALSO: Archaeology and the Present; Community Heritage; Heritage and Conflict Resolution; Heritage and Politics; Heritage and Value-Based Approach; Heritage Ethics

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Heritage and Landscapes

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Landscape is experienced and conceived of in many different ways. In its broadest sense, landscape may be defined as a cultural or mental construct, a terrain adapted, constructed, or modified by people, or a direct result of natural processes. This entry focuses on the third and last definition, while keeping the other meanings in mind; and it focusses on European examples.

“Landscape includes everything, natural and human, that makes an area distinctive: geology, landform, soil, plants, wildlife, and patterns of human land use. It can be viewed in different ways, depending on the different natural and cultural values of the observer” (Stace and Larwood 2006, 11). Indeed, landscape has been given a variety of meanings and definitions and can be quite different for diverse observers or academic disciplines. Geologists, archaeologists, and historians each use different scientific definitions and descriptions, while landscape users have their own interpretation, which is dependent on the observation of their own environment. European city dwellers observe a colorful and variable landscape more or less unconsciously, as part of everyday life, but underneath the layers of urban building, agricultural fields, and infrastructural patterns a whole world of geological variability and natural diversity is present of which most people have no knowledge.

This is partly because Europe’s inhabitants have been disconnected from the natural world for more than a century (and even for longer in some countries), as a result of the fact that the Industrial Revolution dramatically changed the landscape (Fuchs et al. 2015). In daily life, people have very little awareness of the sometimes spectacular processes and remarkable shapes that underline landscape and are contained in the ground below their feet. All places on earth, however, have an identity that is grounded in

the rich heritage of landscapes, rocks, fossils, and mineral sites. To enrich society and to communicate the power of breathtaking and magnificent natural phenomena, it is necessary to (1) highlight the rich invisible geoheritage that is often linked with biodiversity and cultural heritage, (2) bring across the different meanings of the phenomenon called “landscape” both to landscape professionals and to the general audience, and (3) add landscape as heritage to the list of items to take care of in a sustainable world that will be resilient to future environmental and societal changes.

The task of making people aware of the landscape around them is an important one. With deeper knowledge and understanding, people will act more positively for a sustainable future for our planet, being aware of the natural diversity and beauty around them, realizing the long-term formation and development of their landscapes, answering to a sense of pride of their region, and thus accepting landscape as heritage. This entry offers three examples from the Netherlands and part of Belgium in northwest Europe. They come from mono-, inter-, and transdisciplinary perspectives and all three treat landscape as heritage.

Case study 1: The disguised beauty of the landscape of the Netherlands and the North Sea: a monodisciplinary approach

The landscapes in the northwest European lowland represent a diverse assemblage of forms, materials, and ages. The events and processes related to land ice, sea, rivers, wind, fault movements, and peat formation, combined with human impact over time, have resulted in a diverse gradation of these lowlands (Figure 1). Usually this variety is threatened: the relatively flat land has been flattened even further through (agro)industrial or urbanization pressures (Kluiting and Rijdsdijk 2013).

While the southeastern province of Limburg and the Campanian high ground in Belgium are characterized by hilly topography that, in places,

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Figure 1 The North Sea coast: sea, surf, beach, and coastal dunes around the island of Schouwen (province of Zeeland in the southwestern Netherlands).

reaches about 350 meters and the hills in central Netherlands rise up to 100 meters, the rest of the Netherlands is a lowland area. A great proportion of the people living here have been raised with the knowledge that they live below sea level, and they experience the landscape as dull and flat. But a closer look at the flat meadows shows the careful observer that the terrain is surprisingly variable and diverse; for example, it has subtle elevation differences (in decimeters) that create sandy hills and minor curvy valleys. Conspicuous land forms—such as old sanded watercourses, crevasse systems, silted estuaries, and ledges of buried dunes—break the often rectangular patterns of the domesticated landscape. Those who use this apparently flat land either for recreational or for economic purposes must be alert to the diversity of the soil: clay, silt, sand, peat, and gravel alternate in space. They bear witness to fascinating processes related to land ice, rivers, sea, peat formation, wind, and faulting. Clear evidence of the forces of nature lies directly underneath your feet.

The largest part of the Netherlands and of the adjoining region of Flanders (Vlaanderen) in Belgium originates in the Quaternary, when it was a giant shared delta of several great rivers that transported erosional products from the European mountains to the North Sea. In the

last millennium, as a result of human-made dike systems, river deposits have scarcely contributed to land-forming processes. Soil lowering, compaction of drained peat polders, and sea level have considerably influenced the security of the coastline. On the North Sea coast the land surface is protected by a large row of coastal eolian dunes, which directly shelter the current population. This row of dunes originates in sand delivered by the sea, then blown by the wind and made into hills. In many places it is now reduced to a narrow sand dike, preserved through human effort for protection against expected sea-level rises in the twenty-first century.

Glaciation—which shifted masses of white-blue ice, hundreds of meters in height, arriving from Scandinavia—turned the original river delta upside down. The basal shifting resulted in the deposition of boulder clay and erratics and in the creation of moraines. This belt of ice-pushed ridges continues under the North Sea but is slightly eroded by waves and currents with distorted layers at the bottom of the sea, including large buried glacial valleys that are the only witnesses of ice ages. Fishermen lifted countless findings from the seabed: bones of giant deer, aurochs and mammoth, and human-made artifacts of bone and flint. More recently, remote

sensing of the seabed testified that the North Sea was an important dryland area inhabited by our ancestors only a few thousand years ago.

Wind is a characteristic feature of the landscape in the lowlands and in the North Sea; hence there are currently many plans for large wind energy parks in the area. Evidence for the force of the wind in the past is also clear. The battle against sand drift in the cover-sand landscape was not always won by the people. It so happened that sand drift transformed certain areas into parabolic dunes, not accessible to humans and declared uninhabitable for many centuries.

Faults and tectonic forces uplifted many parts of the European continent; and some of the North Sea has been heavily subsided over time (by more than 600 meters). These vertical and lateral movements of the upper earth's crust cause earthquakes that can be felt in many different places in the southern part of the region; thus in 1992 an earthquake of 5.8 degrees on the Richter scale caused considerable damage at the fault in Roermond.

Case study 2: The drowned landscape of West Brabant, Netherlands: an interdisciplinary approach

In the western part of the Dutch province of Noord-Brabant, Pleistocene sandy soils are dominant on a relatively higher platform, which slopes down gently to the north and more steeply to the west, where mainly clayey soils and remains of peat occur, lying slightly above sea level. On both soil types, agriculture was the main form of land use, although some parts of the sandy soils are covered in woods. There used to be large-scale peat quarrying in the region; it was done mainly for fuel in the sandy areas, while peat was also quarried for salt in the lowest areas. The region is bordered by the river Scheldt to the west and by the estuary Hollandsch Diep to the north, while several smaller rivers and streams drain its larger northern area. Three motorways and two railroads intersect the region today, as the waterways and many small market towns of the past have expanded. The northern clayey area remains an open landscape, but the sandy higher part has become more densely wooded over time.

The history of this region is characterized by two settlement periods, one medieval and one modern. Long-term flooding has affected the lowlands' landscape tremendously. Large parts of the flooded areas were eventually covered with a thick layer of clay, which also covered most of the medieval settlements and large parts of the old infrastructure, freezing it in time. In other parts the flooding was quite destructive: new channels were formed that completely washed away all archaeological remains. Then a second settlement period began by gradual reembanking the flooded lands. This process was completed by the end of the nineteenth century.

Specific historical features of the vanished landscape of this area have been used as key features in the plans for its redevelopment as part of the 1990s Dutch national landscape policy called 'Belvedere' (Kluiwing, Brand, and Borger 2006; De Kraker and Kluiwing 2008, 2010). The redevelopment began with an unravelling of the history of the landscape by documenting possible locations of settlements and infrastructure from the first settlement period, as well as by exploring general geological and archeological features; these were checked through remote sensing, by taking aerial photographs on different flights. After the inventory, a selection of four high-quality locations was made. Here physical geographers, archaeologists, and cultural historians went into the field or into the archives and did more detailed research on the vanished landscape. Fieldwork in oral history was carried out to explore the stories and recollections of the present inhabitants with respect to flooded villages and landscapes.

All these disciplines, combined, delivered a general picture of the history and impact of the flooding. Four key historical locations were identified, next to other drowned settlements: (1) Polre, with all archaeological remains in the subsoil still preserved; (2) Hildernisse, an excellent example of a flooded site that survives today and preserves many remains in the soil; (3) Niervaert, completely wiped out by erosive forces but still remembered for its worship of relics; and (4) Koevering, a short-lived settlement on a dyke, whose precise location still has to be worked out (Figure 2).

The next stage involved discussions between landscape experts, designers, and planners. The



Figure 2 The map of Christiaan's Groten, sixteenth century (Royal Library Albert I, Brussels), shows West Brabant (right side of the map) as part of a drowned landscape. At the front, the designer's scenario for the flooded village of Koevering is visible.
Source: From Kluiving, Brand, and Borger 2006.

kickoff was an introductory trip to the field, which was labeled “looking at grass meadows with nothing in them.” From then on four meetings and seminars were held where participants could exchange views and learn about the results reached up to that stage. The project's structure gave designers and decision makers the opportunity to form an idea of the process of research and of how various disciplines operate and to witness every step of the process. At the same time, it gave researchers valuable clues as to the kind of information that designers and decision makers really needed for the task of redeveloping the rural landscape.

The designers preferred practical information and spatial patterns with landscape as a binding factor. They did not treat the findings and the results as the researchers had expected. After picturing the development of the landscape in general patterns in time and space, the final product resulted in a “design” matrix. This matrix offers development strategies and opportunities to include spatial and historical features of the landscape at three levels: local, subregional, and regional. At the same time the matrix shows how the historical features of a vanished landscape

can be used as an inspiration for a museological scenario, as a driving force for a scenario related to the economy (building and tourism), and as part of a scenario for water. The application of the design matrix must lead to a redevelopment of the rural landscape that enlivens the drowned landscape as an important part of the heritage—one that restores the character of this lowland region (Kluiving, Brand, and Borger 2006).

Case study 3: Landscape as heritage for future directions: a transdisciplinary approach

The landscape just described—the drowned and vanished West Brabant—reflects a typically Dutch theme: the battle against water. The great diversity of geological processes and resulting landscapes is unparalleled in the world and has had its impact on the region's cultural and economic history, shaping the reality of today. Because of this, there are currently plans to seek UNESCO Geopark status for the transnational region from the Dutch Hollandsch Diep in the north to the

Belgian city of Antwerp in the south, to mark its geological, ecological, and cultural–historical richness. Global Geoparks are single, unified geographical areas where sites and landscapes of international geological significance are managed through a holistic concept of protection, education, and sustainable development.

Geological phenomena in the Scheldt region, around Antwerp, Belgium, and in the southern Netherlands testify to a dynamic landscape that shows a wide range of geological processes, from very old to very young. Local Tertiary exposures around Antwerp show 33.9-million-year-old Oligocene marine clay deposits as well as a 3-million-year-old Pliocene beach sediment witnessing coastal beach conditions. In contrast, directly north of the Nieuw-Namen site, a modern-day tidal regime is present in the (Drowned) Land of Saefthinge, where tidal flats are still being actively deposited on the flanks of Westerschelde. The Brabantse Wal escarpment is another unique geomorphological structure; it has a steep slope with an elevation difference of up to 25 m that can be followed over more than 30 km. In this slope 1.8-million-year-old tidal deposits of Tiglian age are exposed, covered by eolian dune deposits that were blown out of the Scheldt valley west of the escarpment during the late Weichselian. The hiatus between the two units is demonstrated by a thin gravel bed that reflects the long period of Middle and Late Pleistocene erosion during which the escarpment was formed through the fluvial erosion of the Scheldt river. The medieval marine flooding caused by human occupation and drainage and leading to peat shrinkage explains why large parts of the flooded landscape (most medieval settlements) were eventually buried beneath a thick layer of clay. The geological history of this region—combined with the cultural history of more than 100 drowned and buried medieval settlements and landscapes reclaimed from the seventeenth century onward by polder building—makes this a highly significant region.

The Brabant Geopark will incorporate both geological–natural aspects and socioeconomic (sustainable) development, along with innovation and cooperation between governments, knowledge-based institutes, and local business and industries. The road to UNESCO Geopark status will help catalyze innovative initiatives

and developments in the region, including the application of the design matrix. Main drivers of innovation in the region are the biobased economy, maintenance, advanced logistics, care innovation, agrobusiness, and social innovation.

Conclusion

Landscape viewed as heritage and the extremely long-term geological and archaeological story of Dutch landscape have been exemplified in this entry with three case studies at (trans)national and regional levels, from the Netherlands and adjoining Belgium; but of course the lessons are to be taken at the global level. Making people aware of the landscape around them and of possible futures has never been more important. For several years now, a scientific and even societal discussion has been taking place around the proposed concept of the Anthropocene. Many scholars agree that we currently live in the Anthropocene, even if they are still debating the date at which an epoch of this name can be said to have started (see, e.g., Waters et al. 2016); and popular awareness of the long-term nature of the process that amounted in the formation of our landscapes, as well as informing our sense of identity, belonging, and pride, will hopefully encourage a positive approach to creating a sustainable future for the planet.

SEE ALSO: Archaeological Sciences;
Environmental Archaeology; Geoarchaeology;
Heritage and Sustainability

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Heritage and Nationalism

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Heritage is a human construction that reflects and embodies a range of human–natural–territorial interactions. In particular, it is currently widely conceptualized as a contemporary product shaped from history, a social and cultural process conditioned by its sociopolitical context (Harvey 2010; Tunbridge and Ashworth 1996, 20; Smith, 2006). Archaeology plays a crucial role in the development of the public policies and practices that define this social and cultural process. In consequence, concepts of heritage develop and change according to relationships between power and archaeology in different political units or states. In western concepts of heritage, places are defined as “historic environments” and artifacts as “cultural resources” or “symbolic capital.” These notions have been used extensively in the construction and legitimization of nations and nationalism during the nineteenth and twentieth centuries.

Nationalism is a political doctrine or an ideology consisting of a framework of ideas, beliefs, and notions that precede the formation of the nation; its aim is the nation’s political self-determination. Two main types of nationalism have been distinguished by scholars: civic or political nationalism and cultural or ethnic nationalism. The first, civic or political nationalism, emerged in the late eighteenth century and was characterized by an ideology. It associated the nation with a universal recognition of individual rights and sovereignty (Diaz Andreu 2007). The French Revolution of 1789 and the Enlightenment are regarded as key movements in the development of nationalism as constitutive of state power and legitimacy in western Europe. They promoted an ideal of replacing the aristocratic order with a more democratic conception of egalitarian community of “citizens,” which formed the basis of

the nation. The nation was perceived as a horizontal community made up of thousands or millions of participant members, with specific territorial boundaries that had the right to constitute a political entity. However, there was a conservative reaction to these ideas in the late eighteenth and early nineteenth centuries; even in Europe, let alone elsewhere in the world, not every country followed this path until later. The second type, ethnic or cultural nationalism, developed in the mid-nineteenth century, although some roots can be traced earlier, to liberal nationalism. It defined nations as units created by people who are part of the same ethnic group.

National communities are regarded in the existing literature as being “imagined communities,” because their members would never know or meet most of their fellow members, but in their minds they are part of a community (Anderson 1991, 6). Macdonald (2003, 2) argues that, since individuals could not identify with their national community through social relations, the process of identification had “instead to be cultural, a matter of shared knowledge and practice, of representation, ritual and symbolism.” Nations were founded upon the articulation of ethnic groups’ distinct heritage, on the basis of a homogeneous culture and sentiments of belonging and brotherhood. The foundations of national identity were created through common history, shared language, and distinctive cultural characteristics and customs. This process of constructing national identities entailed the acts of forgetting (or misremembering) and inventing (or rediscovering) chosen aspects of the ethnic group’s past. Thus ethnic or cultural nationalism created the essentialist and primordialist accounts that traced the origins of ethnic groups, their claims on a territory, and their cultural characteristics from remote antiquity to the present day—and these provided them with the right of self-government.

The nation’s past and its narratives of origin were articulated by the material remains found within the state’s jurisdiction. These material remains do not have an inherent meaning, but rather become meaningful and valuable through

contemporary cultural processes that identify them as material symbols of bound and exclusive national cultures. Cultural historical archaeology or (by a different name) nationalist archaeology emerged in the last quarter of the nineteenth century in Europe and legitimized nationalism by providing scientific evidence for the origins of the nation and for its continuity. It documented and interpreted the archaeological record of specific people with the aim of tracing its geographical and chronological differences from other peoples; this replaced the previous emphasis on temporal variations that was based on Darwinian evolution (Díaz Andreu 2007). The focus shifted from identifying stages of development to distinguishing particular archaeological cultures and their features. By making this shift, cultural-historical archaeology created the founding histories of the nation-states: it based their territorial rights on histories of origin and on the long-term continuities of a homogeneous culture. This process led to the justification of the political autonomy of the nation-state as it traced its ownership of land in a linear mode, from the present to ancient times. Public museums in Europe assumed the role of both educators of the citizens and historical anchors of the nation: they located and developed the distinctive qualities of national identity through linear and comparative displays (Macdonald 2003). The concept of otherness was, and still is, fundamental in the material representation of national narratives in museum galleries, since identities were constructed in juxtaposition with the perceived other. Material culture's physicality gave these notions a sense of material reality. Museums were thus transformed into poetic and political spaces whose displays were acts of cultural symbolism: they provided the scenography and stage for the performance of nationalism as the universalized myth of nationhood.

The national appropriation of heritage

Societies attribute to particular time periods an idealized historical experience that they see as the symbol of their nation-state, and the material remains from that era acquire the status of national heritage. Antiquity and its material remains have traditionally been a key anchor

point for different nationalisms and their political aspirations, as they provided a sense of historical and territorial continuity. Ireland, for example, constructed its national identity during the eighteenth and nineteenth centuries, by appealing to the ancient ideal of a pre-Christian self-governing Celtic culture at first and, next, of an early medieval culture that fused pagan Celtic traditions with Christianity. A national imagery of medieval monuments, artifacts, and picturesque landscapes was formed; it depicted a glorious and independent past, which contrasted with the colonial present of nineteenth-century Ireland. Nationalist movements in Spain (Castilian, Catalan, Basque, and Galician) authorized their causes through archaeological discourses that traced the distinctive linguistic and cultural components of their respective populations from pre-Roman times to the medieval period (Díaz Andreu 2007).

A particularly good example is Greece, where ancient material remains became symbols of the nation *par excellence*; in particular, classical architectural remains structured the topos of the new nation-state during its formation in the 1830s. Encounters between residents of the Hellenic peninsula and the traveling western European upper classes, for which Greek classicism was the symbolic capital of European Enlightenment, played an important role in the rediscovery of a Hellenic heritage (Hamilakis 2007). The support offered by the European elite to the Greek cause of liberation from the Ottoman Empire and self-determination was based on the status of Greece's classical past as an ancient entity whose glory had to be restored. This idea was appropriated by the Greek state and formed the new indigenous ideology of the Hellenic nation, a centralized and homogeneous imagined community defined by its glorious past, with Athens as its national capital. The topography of the Greek nation was founded upon classical buildings and material culture, treated as material landmarks of the new national community of Hellenism, and, along with Greek language, offered a sense of territorial and historical continuity with a classical and idealized past. Until the nineteenth century, the ancient site of the acropolis was a symbol of ancient Athenian hegemony, and during the formation of the Greek state it acquired its enduring status as the sacred symbol of democracy and of high cultural achievement. Prehistoric remains,

the Hellenistic and Roman past, Byzantine churches, Ottoman architecture, and vernacular houses retain an ambiguous status within Greek national imagery even today. The protection of ancient monuments became a priority for the new Greek state, and by 1834 all antiquities were regarded in law as national property; their conservation and the regulation of the export of artifacts were seen as matters of national duty. The centrality of this narrative within the national imagination of Greece is still evident in the claims for the repatriation of the Parthenon (or Elgin) Marbles, an eminent symbol of the Greek nation. This idea of heritage as cultural property of the national community is central to western conceptions of national identity, as it raises the issue of rights of territorial and historical ownership. Indeed, heritage restitution has become a key policy under the auspices of UNESCO among former European colonies that created new states within the twentieth century and whose material culture was collected by foreign travelers and museums during the nineteenth century. The state-sanctioned heritage management and conservation practices symbolically constitute the nation as a real and legitimate entity. The western idea of heritage as physical evidence of national cultures entails the archaeological practices of mapping, preserving, and conserving, which are authorized by national legislation all the way from early examples such as Sweden's statute for protecting antiquities—which was passed by King Gustavus Adolphus in 1630 and became law in 1666—and the Ancient Monuments Preservation Act of 1882 in Great Britain to contemporary international agreements and charters such as those of UNESCO and the Council of Europe. This relationship between archaeology and nationalism remains vibrant today, and heritage in the form of antiquities or ancient architectural remains still acts as a key anchor point for cultural nationalisms. Archaeological narratives and concepts or practices that are incorporated in heritage management policies, such as authenticity, create exclusive scientific and hierarchical categories on the basis of which archaeological collections are understood and become meaningful. In particular, the concept of archaeological authenticity becomes the cultural choice for fixing points of bounded national histories on the basis of a fundamental belief in

a sacred national and moral self that provides security in an amorphous society. The foundation of these authentic points of security is the body of knowledge that derives from an artifact's provenance, namely the archaeological context of its excavation, which fixes the meaning of material culture and positions it within the national imagery.

Even ordinary, commonplace, or typical archaeological remains can be recruited to support a national narrative. The authoritative meaning of the Bronze Age site known as Broad Down (in Devon, England) has been fixed by its official designation or production as a monument of national importance. Through heritage management schemes, statutory documentation, and interpretation boards on site, Broad Down was transformed from a typical prehistoric site used for farming purposes by local people in the twentieth century into a fragile site that required saving for future generations. The site is recorded on the Historic Environment Record (HER) and has been described as a prehistoric ritual landscape unparalleled in Devon for its national archaeological significance. This preservation process not only gave it a monumental quality but also imposed a rationality upon the site: it became a material record of constituting the national present, whose purpose is to enhance the quality of the life of the members of the nation (Harvey 2010).

Such official discourses of a homogeneous national identity in Britain can, however, be disrupted through precisely the same legal and practical processes. The narratives surrounding the Hilton of Cadboll, an early medieval cross slab in Ross and Cromarty, Scotland, have considerable contemporary symbolic capital in representing a distinctive Scottish national heritage within the supranational entity of the United Kingdom. The slab represents the high art of Scotland and is associated with a formative period in the history of the Scottish nation (mid-eighth century to early tenth century; Jones 2005). This cross slab is embedded in discourses of "belonging" and mediates the production and negotiation of the Scottish identity: it has a symbolic status as a living member of the local community. The local discourse of belonging surrounding the Hilton of Cadboll creates a relationship between the monument and the

Scottish community understood in terms of birth, soil, and kinship and expressed in claims such as “the Stone belongs to us.” The metaphorical and symbolic meaning of the monument encapsulates the idea that people belong to a place by virtue of belonging to the local community, as it embodies that place. The nation as an official power of the state constructs a hegemonic “authorized heritage discourse” that attributes an inherent cultural significance to material remains of the past and creates a consensus version of history. This approach to the past is used to support or contest the claims to territorial sovereignty of particular ethnic groups (Tunbridge and Ashworth 1996). This makes heritage dissonant and contested, a potentially divisive force that contributes to intolerance, to the marginalization of those who do not “fit” into the official national culture, and to conflict. For example, the dissolution of the Soviet Union and the consequent restructuring of the new nation-states in eastern Europe in the 1990s led to territorial and proprietary claims, which were based on the different interpretations of the ancient past and of the archaeological record. This use of the historic environment and archaeological remains can escalate to violence and may lead to the intentional destruction of heritage monuments, as witnessed in the region of former Yugoslavia during the war in the 1990s, or evidenced by the recent terrorist assaults carried out by Daesh on the archaeological site of Palmyra in Syria. Another example of how heritage, embodying different values, can be manipulated by different groups of people, for different political objectives, is the Taliban’s destruction of the statues of Bamiyan Buddhas in Afghanistan in 2001. The international community had for some time proclaimed the universal value of these sixth-century statues as part of the shared heritage of humanity. The Taliban’s radical clerics perceived them as representations of non-Islamic “impurities” that had to be eradicated from the country. The idea that the traditional approach to heritage as a valuable asset in need of preservation can lead to political conflict is also illustrated in the case of the Preah Vihear temple in modern-day Cambodia. This temple, a great example of Khmer architecture from the tenth and eleventh centuries, has become a contentious landmark of the opposing political claims between Thailand and

Cambodia. The Preah Vihear temple, along with other major temple sites, such as Angkor and Banteay Chhmar, was under Siamese possession until the late nineteenth century. The contemporary Thai government puts forward political claims that are based on the ownership of these archaeological sites. UNESCO’s listing of the temple and its immediate surroundings as a property of Cambodia in the World Heritage List in 2008, even though it covers land disputed between Thailand and Cambodia, caused a significant political controversy between the governments of the two countries over the sovereignty of the site and its adjacent area.

These examples show that cultural heritage is still appropriated by national governments to either support or dispute territorial and historical claims. Hence the consensus in current literature is that a critical understanding of heritage and of its relationship with nationalism necessitates the analysis of the nature of heritage: what it is, the process of its construction, and the cultural, social, and political work it does in current societies.

SEE ALSO: Authorized Heritage Discourse; Community Heritage; Cultural Resources Management; Ethnoarchaeology; Heritage: Nonwestern Understandings; Heritage and Conflict Resolution; Heritage and Landscapes; Heritage and Politics; Heritage and Society; Heritage Interpretation

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Heritage and Policy

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Already from its appearance as a notion, heritage has had a political connotation. The concept emerged in Europe—and particularly in Britain, France, and Germany—within the context of nineteenth-century modernity. In this context of Romantic nationalism, new metanarratives were sought that could bind populations to a shifting sense of territorial identity and legitimize state formation. Heritage, archaeology, and the past were used to sustain these narratives and to reassert symbolic and physical borders in order to validate differences between countries and populations. Many of the newly established European states started to engage in conservation and management activities, which led to a canonization of landscape, folklore, and historic sites and to the establishment of national museums. It also led to the establishment of a preservation movement that had to make sure that the physical representations of national identity, European taste, and achievement were protected and displayed to the public. This movement advocated the so-called “conservation ethic,” a paradigm that would have a long-lasting effect on heritage policies. It stressed the trait of heritage as a limited and threatened resource and the importance of preserving resources of the past as material and scientific markers. Heritage needed to be protected for future generations, and this became an accepted and expected task of governments.

The institutionalization of this conservation ethic formed the basis of the first heritage policies. While the first legal decree to protect national antiquities dates to the seventeenth century in Sweden, the second half of the nineteenth century saw an upsurge in the development of legislation designed to protect ancient monuments and religious or other architecturally and historically significant buildings. Both architecture and

archaeology—due to their ability to claim professional expertise over material culture—took on a pastoral role in identifying the appropriate monuments to be protected under these acts and in caring for and protecting these places (Smith 2006, 19). In these first legal acts the emphasis was on preservation. This meant that heritage was defined according to whether the corresponding entity was at risk. Preservation literally meant protection of heritage from harm. It focused on the fixed quantity of historic resources, not on their perceived functionality. The idea of monumentality was leading, which meant that the cultural significance of a site, building, artifact, or place determined its use and management. This cultural significance was established by experts who valued heritage in terms of its historical, scientific, educational, and “cultural” value. The introduction of this conservation ethic was not limited to the western world. Archaeological thought and concerns over the care of cultural remains came to be exported globally, as part of colonialism and imperialism (Byrne 1991). For example, in the early twentieth century, heritage and monument laws were introduced in the Dutch East Indies and in British Indochina and India. These laws led to the selection and interpretation of indigenous heritage within western frameworks of understanding and categorization; they were focused on preserving or restoring monuments for the educational or scientific benefit of a public at home in Europe (Fienig et al. 2008, 33).

The conservation ethic remained a fundamental part of the institutionalized heritage management discourse and of political and legal frameworks in Europe during the twentieth century. This resulted from continuing Western nostalgic concerns about the potential loss of identity and traditions in an insecure present. Moreover, the rise of cultural tourism and the “heritage industry” in the 1950s and onward led to a questioning of authenticity. Additionally, the appearance of environmental concerns in the 1960s and 1970s and the rise of a general awareness, in the 1980s, that remains from the

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past were under threat from development forces called for a renewed focus on preservation. Thus, in 1965, the ICOMOS Venice Charter was adopted, which emphasized ideals of authenticity and the maintenance of the historical and physical context of a building or site. This growing awareness about new threats to the past led to the replacement of the notion of preservation by the notion of conservation. This transition did not involve a radical break with previous approaches to heritage. It primarily meant a broadening of heritage as a notion. Not only buildings were to be preserved, but also ensembles. Furthermore, sites, buildings, artifacts, or places became selected not only through intrinsic, but also through extrinsic criteria. Thus heritage management no longer entailed primarily an investment in form, but also one in function. From the 1990s onward, conservation became related to land-use planning systems, which resulted from a consensus that the protection of the historic environment was a fundamental purpose of planning policy. This change led to the adoption of several new policy documents and legislative systems at the national and international level. While until then heritage policy had been largely the preserve of architects, archaeologists, and art historians, from that point on it was integrated in more extensive schemes of local area renovation, revitalization, and regeneration. Hence the experts were no longer the ones making decisions about preservation, but politicians and government officials increasingly started to take up this role (Willems 2010).

This increased emphasis on the functionality of heritage influenced not only the ways in which heritage was defined as this concept was increasingly broadened, but also how decisions were made, what interpretations were given to heritage, and how management practices were organized. There was a clear development toward contextualizing individual sites and monuments as part of a larger whole—the historic environment—and toward a realization that the sustainability of that larger whole, rather than the conservation of individual monuments or sites, was a key objective of heritage resource management (Willems 2010, 216). The historic environment was now being studied, evaluated, and defined in terms of its history and its present-day relevance to people. Additionally, heritage became fashion-driven.

New presents constantly asked for the imagining of new pasts in order to satisfy changing needs. At the national level, the policy context around heritage became more developed, more complex, and more explicitly linked to other policy goals, for example, economic regeneration, social inclusion, and localism. Heritage was less about tangible material artifacts or other intangible forms of the past than about the meanings placed upon them and the representations that were created from them (Ashworth, Graham, and Tunbridge 2007). Moreover, international organizations took up this broadened notion of heritage in their main conventions. In 1972 UNESCO adopted the notion of “the importance of heritage to humankind as a whole.” Additionally, during the 1980s and 1990s the Granada and Valletta Conventions introduced the so-called “landscape approach” and “integrated conservation” as a means to guarantee a more sustainable way of protecting heritage. This meant that professionals with different kinds of expertise, such as architects, landscape architects, and planners, would work together on joint projects.

Despite these trends in heritage policy and shifts in the interpretation of heritage, the conservation ethic never completely lost its relevance—not only in the 1990s, but even up to the present day. The preservation of cultural remains as markers of an uninterrupted past has continued to affect heritage policies at the national as well as at the international level. Moreover, state policies, professional expertise, and supposedly objective valuations of materials from the past are still determining most of the decision-making processes around the care for cultural remains. This trend came to be increasingly criticized in the 1990s. The hegemony of Western values in heritage management was addressed, as well as the “authorized” heritage discourse that favored professional, governmental, objective, and expert approaches to the past over subaltern and alternative heritage discourses and historical narratives (Smith 2006). The critical accounts pointed to the unquestioned conservation ethic that was underlying the heritage management approaches in the Western world and continued to determine most international heritage policies and scholarly debates. Additionally, they urged for an acknowledgment that not only the past, but also the valorization

of cultural heritage was socially constructed (see, e.g., Byrne 1991). Awareness was growing that heritage management was thus not so much about the preservation of archaeological and architectural remains as about the social values attributed to them. This prompted an appeal to take into account, in heritage management and policy, the values and interests of other stakeholders and not only those of professionals, experts, and policymakers.

In this frame new charters and policies appeared that tried to accommodate different approaches to heritage management. In the United States, for example, the Native American Grave Protection Act (NAGPRA) of 1990 introduced procedures and legal standards for the repatriation of Native American human remains, funerary objects, and cultural patrimony held in museum collections. In Australia the ICOMOS Burra Charter was revised in 1999. In the revised version, “associations and meanings” were presented as a part of cultural heritage that stood next to material artifacts. Two fundamental characteristics of these American and Australian heritage policies were subsequently adopted at the international level. The first one concerns the emphasis on heritage diversity and community participation. The second one focuses on the ideological concept of valuing the resources of the past by identifying and assessing significance and stakeholder values (cf. Lafrenz Samuels 2008). These value-based management models are currently the basis of the policies, charters, and guidelines of international organizations such as ICOMOS, UNESCO, the World Bank, and ICROM. The adoption of the ICOMOS Nara Document on Authenticity (1994), which explicitly recognized cultural and heritage diversity, is one good example of this. The set of UNESCO guidelines for managing world heritage sites by means of value-based planning is another example. Additionally, professional and ethical codes of conduct were introduced on how to incorporate the values of others in society into professional conduct in the implementation of heritage policies.

In Europe, value-based significance assessments became part of heritage policies, especially in the framework of the new legislative frameworks adopted as a result of the Valetta Convention of 1992. However, these initially paid less

attention to questions of community participation and alternative heritage values—an issue well reflected in European codes of conduct, which are primarily expressions of ethical concerns related to contract archaeology and show less interest in issues such as repatriation, human remains, and the involvement of indigenous voices and values (Aitchison 2007). Nevertheless, the last decade has witnessed important moves in this direction, illustrated for instance by the rise of community archaeology in European countries such as the United Kingdom and by the 2005 Faro Convention on the Value of Cultural Heritage for Society by the Council of Europe. Attention is increasingly paid to what ordinary people consider to be heritage; and, in line with this, there is a decentralization of heritage (or democratization, as some argue). In other words, heritage management and its affiliated policies have started to move away from fairly authoritarian and centralized decision making and toward concerns for social inclusion; local stakeholders and communities are involved in dealing with the historic environment (Fairclough 2009). This shift occurred not only because it was acknowledged that stakeholders and communities have a big influence on the sustainable preservation of that environment, but because it was recognized that they have an actual stake in heritage projects. As the title of the Faro Convention reveals, the attention has become directed to the “value of cultural heritage for society.” Heritage came to be presented as a resource for human development, for the enhancement of cultural diversity, for the promotion of values such as democracy and peaceful societies, and for the stimulation of socioeconomic growth. Different types of values were attributed to heritage: intrinsic (i.e., heritage is valuable by itself, as an enrichment to the landscape in which it is located), institutional (heritage as a catalyst for communal action), instrumental (heritage as a contributor to social objectives such as education, or to the development of certain skills), economic (heritage as an asset that can generate financial revenue for the benefit of governments), and even reconciliatory (heritage as an instrument in postconflict actions).

These changes in the interpretation of heritage policies reveal that in the past decades a paradigm shift has taken place. There has been a move from

the expertise-led and object-oriented preservation paradigm rooted in the “conservation ethic” to an inclusive and people-oriented new heritage paradigm. This paradigm shift is not yet been fully concluded. Vestiges of the conservation ethic still determine heritage policies at a national and global scale. However, there is a move to a “dialogical model” (Harrison 2012) in which heritage is seen as emerging from the relationship between people, objects, places, and practices. This model does not distinguish between, or prioritize, what is “natural” and what is “cultural,” but instead is concerned with the various ways in which humans and nonhumans are linked by chains of connectivity and work together to keep the past alive, in the present, for the future. The model presupposes an ethical stance in relation to others and a belief in the importance of acknowledging and respecting alternative angles and worldviews as a condition of dialogue. As such, it provides a way to connect heritage with other pressing social, economic, political, and environmental issues of our time. As some have argued, in this new heritage paradigm there is no place for “canons,” whether national or ethnic. On the contrary, there is a clear move away from monumental (and outstandingly universal) values. Instead, values arise locally, from the grassroots (Fairclough and Wolverstan 2013, 47). Interpretations of heritage have become ever more varied and start to serve a multitude of purposes. Amongst other purposes, heritage is seen as a factor of community building at the national, regional, and international level, an instrument behind socioeconomic development, and a means of bringing about intercultural dialogue.

More paradigm shifts might follow in the field of heritage policy in the future. Several challenges lie ahead that will ask for a continuous rethinking of policies. One of these challenges is the abundance of heritage. Due to the increasingly broad definition of heritage and the exponential growth of listed objects, places, and practices in the contemporary world, there is a risk of becoming overwhelmed by heritage, which would render it ineffective and worthless. Hence one needs to consider strategies for abandoning certain heritage sites and for offering possibilities to remove heritage from museum depots or from lists such as the World Heritage List (Harrison 2012). Another challenge is the dissonant nature

of heritage, which continues to play a role in conflicts all over the world (this challenge is by no means new). Even though heritage can be instrumental to defining communities and cementing the nation, it can also be used as a means of segregation. Even though international organizations such as UNESCO or the Council of Europe have urged for a move away from ideological interpretations of the past and toward more inclusive narratives, they continue to face many obstacles. A possible future development might be to ask for an admission that heritage is not always good or positive, and thus for a distancing from the universal value of heritage (Viejo Rose 2013). Finally, a last challenge that requires a rethinking of heritage policies is the influence of the digital age. Heritage has increasingly been digitized and made available on the web. This has made it possible for museums to display parts of their collections rarely shown to the public, has made heritage available to ever wider audiences, has introduced innovative methods of public outreach and involvement, and has made it possible to preserve photographs and texts without having to deal with the storage. However, it has also raised new questions about how to unlock the potential of digital heritage, how to deal with free access, and how to work on the web, which represents a new frontier of our global culture. These challenges—and many more could have been mentioned—reveal how heritage policy is in continuous movement, being influenced by new challenges and perspectives.

SEE ALSO: Faro Convention; Heritage Management

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Heritage and Politics

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Heritage and politics define how the understanding of, and the values attributed to, a sense of the past are formed through negotiations of power and identity within contemporary society. Indeed, the modern concept of heritage is an invented tradition, born out of the industrial and political shifts that reformed European society from the eighteenth century onward. This concept focused on the significance of monuments and places that appeared to evoke a “national spirit.” Such Romantic allusions were drawn from the earlier work of antiquarians in Britain, France, and Germany, who had examined prehistoric, classical, and medieval artifacts as a means of demonstrating the illustrious origins of kingdoms and the inevitability of royal power. Individuals such as the French scholars Claude Fauchet (1530–1602) and François Roger de Gaignières (1642–1715) or the English historians William Camden (1551–1623) and William Stukeley (1687–1765) carried out extensive surveys of libraries, antiquities, and monuments to provide noble patrons with evidence of their ancestry and thereby with justification for their authority. Places and objects were imbued with significance and their preservation was connected to the continuance of the state and with the form and function of the nobility. The origins of the heritage movement in Europe were firmly associated with the operation of power, as evocative national narratives were formed that cemented social structures. Organizations such as the Society of Antiquaries of London (1707), the Society of Antiquaries of Scotland (1780), the American Antiquarian Society (1812), the Société des Antiquaires de France (1813), and the Gesamtverein der Deutschen Geschichts und Altertumsvereine (1852) focused on genealogy and heraldry to evidence the formation of the state as the pinnacle of achievement.

This function of the past to legitimate and stabilize the present was reiterated during the eighteenth and nineteenth century, when rapid industrialization, urbanization, and imperialism required the strengthening of national narratives as traditional structures of class, gender, and ethnicity were challenged. The American War of Independence (1775–83), the French Revolution (1789), the Chartist movement (1838–57) in Britain, and the German revolutions of 1848–49 all brought an expansion of political representation in the West and revised views of heritage. Whereas once notions of “heritage,” *patrimoine*, or *Erbe* were embedded in the figure of the monarch, now they were invested in the people, as states sought to elicit from their newly enfranchised male citizens a sense of national identity. At the outset of the nineteenth century, romanticized notions of natural and cultural sites of significance were promoted as reflective of “the people.” Literary figures such as Johann Wolfgang von Goethe (1749–1832) or William Wordsworth (1770–1850) extolled the virtues of both national culture and tradition, as “heritage” became emblematic of the state. As part of this process, conservation and preservation movements took place during the nineteenth century in Europe and the United States, as a reiteration of what was important for the nation. In France, the title of *inspecteur général des monuments historiques* was created in 1830; the person appointed to this position had to catalogue the historical environment in the country while the nation veered between a monarchy and a republic. With the establishment of the Third Republic from 1870 on, these *monuments historiques* served as memorials set up by the nation for the people.

The conservation of natural sites followed the same trajectory as cultural heritage: governments concerned with the loss of places of collective identity set legislation to protect areas of “wilderness.” Natural areas were assumed to possess the character of the nation, so their protection from development enabled the survival and promotion of a singular nationalism. In the United States, the Yellowstone National Park Protection Act (1872)

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enabled the preservation of a large tract of land in Wyoming, Montana, and Idaho and in the process defined a distinct “American” character. The legislation protected sites considered to reflect the values of the nation during the late nineteenth century, when the processes of urbanization and mass immigration had been perceived by nativist politicians as a dilution of this character. The democratic state was strengthened through this protection of heritage in response to the challenges of modernity, since the government drew upon a sense of the past to appeal to mass electorates. As western countries used legislation to protect natural heritage, the notion of heritage as a universal good was established during this era. The discourses associated with the formation of legislation and modes of protection in the nineteenth century serve to underline political identities and structures of government while presenting heritage as politically neutral. Heritage as a conservative influence on society preserves political and social systems as much as it ensures the protection of landscapes, sites, and objects of significance. As such, heritage forms the basis of the emergence of democratic nation-states in the West during the nineteenth century (Silverman 2011).

The association of heritage with nationalism ensured that the former served as a means of exclusion and as a means of establishing common points of identification. The concept of heritage formed in the nineteenth century was structured by notions of class, gender, and ethnicity. In Britain, France, and Germany as well as in the United States, to look upon heritage in the form of a landscape, place, or object and to appreciate it fully as a category of value required a male middle-class European identity. With the imperial expansion of major powers in the late-nineteenth century, notions of heritage were used to support a colonial politics that enabled and supported the exploitation of peoples and resources in Africa, the Americas, Asia, and Australasia. The removal of cultural artifacts from colonized areas across the world and their display in the West develops significantly from the eighteenth century on. For example, the military campaigns of Napoleon Bonaparte (1769–1821) in Egypt (1798–1801) triggered a fascination with monuments and artifacts from the ancient sites along the Nile. These were displayed in public places and in museum

collections where audiences could marvel at the past achievements of former empires. This use of heritage supported an imperialist structure of power, because the current inhabitants of these sites were encouraged to sever any sense of connection with this past: the empires of Britain and France appeared to be the rightful heirs of such illustrious forebears. The removal of artifacts (including human remains) from indigenous peoples was also made to serve as the base for a classificatory system of human racial types; cultural heritage was employed as evidence of a social evolutionary scale. The display of objects from traditional societies was used to reinforce notions of racial superiority. At the Great Exhibition of 1851 in Hyde Park, London, the display of people and objects from imperial possessions provided an image of British, European, and western hegemony.

The use of heritage to reinforce nationalism and imperialism in the nineteenth century indicates the significant political role of representations of the past. In the twentieth century, this function of heritage was consistently present, as the turmoil of conflict and dictatorships witnessed the appropriation of heritage to secure power. In Nazi Germany (1933–45), prehistoric and medieval monuments and sites were used to promote the racist ideology of the state. The way this continued the established modes of representation rather than marking a departure from them reiterates the function of heritage within modern society. As a tool of conformity, the recognition and protection of the past establishes the relationship between the individual and the state. It is this connection that has been challenged by the global political changes that have occurred after 1945. In the wake of total war, genocide, and the deaths of millions of civilians during World War II, the connections that societies possess with their own past and with that of others have become a far more contested area of study. With the rise of internationalism, democracy, and postcolonialism, the political function of heritage has been utilized to disrupt western hegemony (Makuvaza 2014). This process can be observed for instance in Ghana, which achieved independence from Britain in 1957. In the same year, a national museum was founded to house the nation’s artifacts and to emphasize its distinctive character

as a modern state. Indeed, the museum was created by the passing of the Ghana Museum and Monuments Board Ordinance 1957, a piece of legislation that also enabled a protective framework for sites of national importance. In India, the granting of independence in 1947 saw the reinvigoration of imperial organizations such as the Indian Museum in Kolkata or the National Archives of India, and the formation of new institutions such as the National Museum in New Delhi, all designed to promote Indian national identity through cultural heritage.

While cultural heritage has been mobilized in this context as part of a nationalist objective, it serves as a response to the undermining of colonized peoples, which occurred as a consequence of imperialism. Conversely, this postcolonial, nationalist use of heritage has developed alongside the formation of an international agenda within heritage practice. The formation of the United Nations Educational, Scientific and Cultural Organization (UNESCO) as a specialized agency of the United Nations in 1945 brought the politics of globalization to what had been a nationalist program within cultural heritage. The Nubia Campaign in 1960 saw cooperation between Egypt, Sudan, and other nations across the world in protecting ancient sites from the development of the Aswan Dam. The promotion and preservation of heritage stimulated the development of international protocols, which in turn have encouraged the concept of world heritage. In 1978, UNESCO's World Heritage Committee began to define world heritage sites, which are regarded as possessing global significance and afforded protection through international treaties. In this manner heritage becomes a tool for global cooperation and diplomacy, as nations recognize the value of the past from other areas of the world and each is accorded the same significance. Heritage acts as a tool of diplomacy, as a means of discourse between nation-states that promotes cooperation, development, and tolerance (Albert and Ringbeck 2015).

However, the concept of *world* heritage and the use of world heritage site status to encourage tourism and economic development have been regarded by critics as a means of alienating indigenous groups from their past while promoting an elite, exclusive global community.

This assessment has grown out of a wider critical perspective in the 1980s that addressed the role of capitalism and of the state in preservation and conservation initiatives (Lowenthal 1985). This critique stated that the presentation of the past within the public sector was an exercise in corporate culture and reduced heritage to a shallow, facile copy of reality that could then be rapidly consumed by its audience. The Disneyfication of history was mentioned by scholars who drew upon a postmodern assessment that emphasized the lack of meaning in late-twentieth-century heritage. The function of this mode of representation within a capitalist society was assessed by scholars to be one of enforcing political passivity while the rights of individuals were ameliorated elsewhere. The analysis of the consumer model of heritage mirrored broader developments, which highlighted the exclusory nature of heritage. According to this assessment, issues of class, gender, and ethnicity had all been implicitly or explicitly removed from representations of the past; heritage was regarded as a vehicle for political suppression. Hence scholars sought to undermine the idea of what constitutes heritage and to argue for a greater variety and pluralism in the public understanding of history. This process of democratization within heritage studies has enabled multiple agendas to emerge that address historic and contemporary injustices.

Heritage as a means of obtaining social justice has become a central component of critical heritage studies over the past two decades. This politically aware approach has sought to explain how groups and communities have been excluded from society through the operation of "heritage." This attempt has also brought a recognition of the wider traditions, practices, and performances that constitute our relationship with tradition (Smith 2006). This disrupts western and predominantly male forms of heritage, which have structured the formation of the nation-state from the nineteenth century. Moving beyond the material base of heritage to encompass the intangible enables a plurality of voices and perspectives to be better heard and seen. The notion of "intangible heritage" has been recognized by UNESCO since 2003, and its employment by scholars has created a greater political role for the field, as this notion disrupts national, gendered, and class-based assessments of heritage. A more inclusive model

of heritage has been formed through a study of both tangible and intangible forms of heritage. However, while growing awareness of what constitutes heritage enables the formation of political identities that might lead to further democratic modes of governance, the ever-expanding list of objects, sites, and landscapes worthy of protection might result in social stasis, as change and adaptation are stifled by a reified sense of heritage.

The preservation of heritage raises broader issues regarding environmental change, sustainability, and adaptability, given that heritage studies are at the center of political debates on how human society continues to live as part of the wider environment (Harvey and Perry 2015). This position has provided heritage studies with a significant role within political ecology, as climatic change threatens the stability and preservation of buildings, places, and cultural practices. However, rather than focusing on the threat posed to heritage sites by environmental issues, heritage can also serve as means to create new political identities, which adapt to loss and alteration because relationships with the natural world in the past can provide new modes of engagement. As the climate alters, the remembrance of our past environment could be the basis of new relationship between humans and nature.

Therefore, within contemporary heritage studies, heritage in its political aspect can be defined as a mode of engagement with the past, the present, and the future that influences four distinct areas of concern:

- national identity, internationalism, and governance;
- communities, dissonance, and empowerment;
- human rights, social justice, and equality; and
- environmentalism, ecology, and sustainability.

These four areas reflect alterations in the discipline as it has moved from being the preserve of the nobility, the instrument of control of the state, and the tool of the body politic. Politics underlines the formation of heritage from the seventeenth century to the present day. The continued role of heritage in the contemporary global society is born out of this relationship with politics. The significance of heritage is not due to

a universal human quality that emphasizes the past and extolls tradition but to the relationship between individuals, communities, and the state: heritage is a political matter. The representation or examination of heritage constitutes an engagement with the political structures that define identity, power, and place in the modern era.

SEE ALSO: Assessment: Heritage Impact (HIA); Community Heritage; Heritage: Nonwestern Understandings; Heritage and Economics; Heritage Interpretation; Public Archaeology

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Heritage and Society

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Heritage and society

Heritage is something that human beings engage with, communicate about, and also make a living from. It has been argued that heritage has always been with us and that it has always been social by being produced by human beings (Harvey 2001). Heritage is everywhere. It is profoundly human to engage in meaning-making activities concerning the material remains of the past. This means that heritage can be everything to everybody. There is nothing intrinsically modern about heritage being social, because all societies at all times make use of their pasts. There can be no heritage that falls “out” of society or is not related to society, so the topic itself is all-embracing, if not defined.

Heritage cannot be viewed separately from its contexts, from its natural and social environments. In social science, a contextual concept of heritage is important. The contextual character of culture is understood through references to a situation in time and place. The relationships between heritage and society can be understood along three dimensions: (1) heritage is internal to society; (2) heritage is socially constructed; and (3) heritage constructs society. Society creates heritage and heritage creates society. It is important to make this two-way relationship explicit to researchers, practitioners, and policymakers alike.

First, heritage is internal to society in obvious and less obvious ways. Heritage is internal to society by appearing as a social phenomenon and as a cultural process. Typically, the term *heritage* often appears in phrases like “cultural heritage” or “natural heritage” and not alone. Both natural heritage and cultural heritage specify that heritage is part of the human domains of reality. Further, the concept of culture is a key to understanding the relationship between heritage

and society. Society is not identical with culture, while culture can be viewed as an aspect of society. Culture refers to the negotiated content of meaning that exists within human societies, and as that which makes communication and meaning possible in society. This shared content is like a map of meaning, a system of language, symbols, and knowledges used by humans. It is through culture, through communication, that societies give meaning to heritage.

Another marker of the social character of heritage is the human or social importance of preservation or conservation—the fact that humans and societies have developed institutions, regulations, and practices in order to preserve or conserve selected remains, traditions, or knowledges from the past. Here there is no intrinsic difference between natural and cultural heritage, as all remains are from the past—tangible, intangible, and digital—with relevance or significance to human societies. Humans ascribe meaning to things, landscapes, memories, artifacts, places, sites, and so on in the present through relationships with remains inherited from the past.

Second, as heritage is social, it is socially created and a product of human societies. This means that heritage is created by human beings and social institutions. The idea of a museum, for example, stems from middle-class society, where the museum was an instrument of national pride and power; particular connections came to exist between the museum idea, class, and progress (Bennett 1995). To understand heritage, we must view it in relation to the social actors and institutions involved in its production and reproduction. So, instead of studying heritage objects and artifacts, we are studying the heritage process or what is commonly referred to as *heritagization*, which refers to practices and processes that create heritage, whereby ownership, knowledge, and recognition are created by local communities and the wider society.

Heritage is interpreted and communicated by humans within particular contexts from particular perspectives (Smith 2006,

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Kirshenblatt-Gimblatt 2006). As societies change and develop over time, it is obvious that the definition of what constitutes heritage changes; what is understood by the term can also change over time and vary between different groups. Societies differ and every society has a different relationship with its past and with the uses of heritage. Within societies, different groups and individuals will interpret heritage in different ways. Some societies or groups within societies have troublesome pasts, and sometimes choose to forget parts of their pasts. There is no absolute definition of heritage in society, so a good start when seeking to analyze and manage heritage is to situate it within its social context and look at its particular and often contested understanding in that context.

Consequently, what heritage is will differ. The nature or essence of heritage, the objects and subjects of heritage are established by ascribing value. Valuation is a social process. The value of any type of heritage is not self-evident but socially constructed. This means, further, that valuation is perspectival. There is someone doing the valuation on the basis of particular values, perspectives, and interests, and valuation is deeply connected to the workings of power in society. It is important to gain a good understanding of the politics of valuation, of actors and interests, of policy contexts, and of how heritage makers have contributed to shaping or making heritage with particular forms of value. What counts as valuable heritage is, consequently, a contested domain in all societies, both democratic and totalitarian. Values are implicitly present when asking questions such as these: Do we want a museum's identity and purpose to be a political symbol for the national heritage elites? Should the museum reflect the worldviews and the *nature* of the museum's objects and subjects? Further, valuation of heritage is not relevant just for purposes related to the present. Valuation is deeply connected to imaginary futures.

This means that there is no single correct and true understanding of what heritage is or should be. There are many stakeholders in heritage, ranging from local populations, visitors, and tourists to enterprises and businesses, organizations, policymakers, and public administration.

Third, as heritage is a social phenomenon, heritage takes place, is shaped, and has effects in a world—in a social world—that consists

of social relations, action and interaction, and social processes. What does it mean that heritage constructs society? Heritage can in this sense be viewed as a landscape, a collective history and geography, a structured totality—much like a *habitus*—that generates meaning and action. Heritage has important effects on human societies. It is central to identity development, to enhancing human well-being and the quality of life, and to improving the way places and landscapes are perceived. It is said to revitalize society, strengthen democracy, and contribute to a more educated and critical public and can be used to improve governance and economic growth. Heritage engages the general public in many ways. In a European context, the Faro Convention places heritage firmly in the hands of human beings by defining heritage a benefit for humans and by linking it to human rights and fundamental freedoms.

Heritage thus contributes to social, cultural, and economic development as well as to sustainable development, which means that we cannot separate development from its contexts. In this sense heritage is also an aspect of development, not only an object or resource for development. As an aspect of development, heritage is always present in human ways of life and livelihoods, so that a people-centered heritage builds identities and supports individual and collective memories and cultural sustainability (Auclair and Fairclough 2015).

The benefits of heritage are well documented, but so are the ways heritage also reproduces social, economic, and cultural differences around the world. For example, the nominations for UNESCO's World Heritage Convention are not ideal or absolute, but related to particular national nominating committees. The end result is that we have a geographically uneven enlisting of what is considered to have outstanding universal values; thus global differences in power are reproduced. Heritage is deeply connected to globalization processes, to how technological and economic development contribute to shaping social life, and to the way power works in society.

Important changes regarding how heritage has been viewed and how it is valued in society have taken place during the past 40 years—the period following the intensification of the globalization of the world economy after the 1970s.

First comes the change from understanding heritage through noncontextual approaches to using contextual approaches—or from object-oriented to constructivist and relational approaches. One tendency has been to focus on constructivist approaches and the social aspects of heritage, looking at heritage in a social context rather than focusing on it as objects with universal or inherent values. This change was influenced by the development of critical heritage studies, and in particular by Laurajane Smith's (2006) *The Uses of Heritage*, which challenged western classical definitions of heritage focusing on the consensual, the pleasing, and the tangible (what she calls the authorized heritage discourse). The new discourse placed a focus on social and societal aspects such as memory, performance, identity, intangibility, dissonance, and place. With provoking sentences like "There is, really, no such thing as heritage," Smith (2006, 13) drew attention to the ways heritage has meaning to everybody in society, and not only to experts and to cultural elites, who traditionally were those who defined what and how to conserve and what to value as heritage.

The debate led to a change from understanding the objects of heritage as "dead" or without agency (heritage as artifact) to understanding them as "alive" or animated by being "social" in a much wider sense. Going one step further, with a different approach, we find ideas of heritage as social in a wider sense, where heritage is relational, collaborative, dialogical, and interactive: it interacts with human and nonhuman agents and subjectivities (Harrison 2015). If heritage is a process, the becoming of heritage is created through natural and cultural processes and represents a totality endowed with diversity and multivocality, an endless, renewable resource open to new interpretations. In this approach, the distinction between what is considered social and what is considered natural or nonsocial is blurred or transcended totally.

The second major change in recent years is a slightly different one. From an economic point of view, heritage has historically been considered a cost to society. Heritage has been a cost in public budgets and a moral duty of democratic, western societies. Recently we have witnessed a shift whereby heritage appears as a vital resource in society. This is a huge change in thinking,

which means more than simply viewing heritage as a means of improving economic performance in a European perspective. It involves turning away from a concept of conservation isolated from use to a new paradigm, which could be described as preservation through use. In this new paradigm, heritage is valued as something profoundly important for improving not only the economy, but also people's lives and living natural environments. Heritage can play an important role for society's overall sustainable development.

This shift reflects the new economy of late modernity, where places, objects, services, institutions, and sites are assimilated into world economy through commodification and place branding. The difference between politics and economics is erased, leaving economics to the ideology of neoliberalization. The marketization of the museum as an institution can transform the museum into a business enterprise where the vocabulary of heritage practitioners changes from exhibition to product. In this scenario, many heritage institutions have or will have more in common with theme parks like Tivoli in Copenhagen and Disneyland in Florida than with the nineteenth-century object-oriented museum.

One challenge for the future is to find ways to frame the relationship between heritage and society that insist on not reducing society to a neoliberal economy and the agents of heritage to producers and consumers. And in the big debate that goes on in our societies as to how to make the world a more sustainable place, in particular after the financial crisis, it is important to find new ways to connect present heritage values to future heritage values.

Current emphasis in research and theory underlines several important aspects, where one common theme is an interest in discussing heritage and society across the nature–culture divide and across the divide between tangible and intangible heritage.

This interest can take many directions. One concerns how global climate change affects the relationship between heritage and society (Solli et al. 2013). How are we going to understand heritage today and in the future, when the world's population needs to find solutions to global social and economic inequalities, environmental problems, and climate change? The division between natural and cultural heritage—which has been

institutionalized in much heritage discourse in society—becomes completely artificial in the light of what some argue: that we not are living in a new geological epoch called Anthropocene. Global climate change is a topic that was monopolized by economics and systems thinking but that affects all of society, and many social and cultural processes are central to climate change by influencing how this phenomenon is perceived and understood. Global change affects the understanding and the definition of heritage and how societies and governments deal with it, which means that heritage policies are often dealt with together with policies for sustainable development.

At a more profound level, the modern worldview was conditioned by a dualist construction of reality, a view in which nature and society were seen as unrelated and had nothing to do with each other because their constitution was different. Society was seen as made up of human beings who think and act intentionally, while nature was most often understood as consisting of various determinate sets of objects and objective processes independent of subjectivity. The objectification of society that came with modernity meant that nature, or the natural environment, was objectified and domesticated. Researchers in the social and human sciences very easily focused on issues of social and economic injustice, power, and class relations within society, while the deeper power relations between nature and society were overlooked. Now this has changed, and in ways that affect how heritage is understood.

The emphasis, in research and theory, on heritage and society is now expanding (Harrison 2015) in a direction of greater openness regarding what and who can “own” agency (operating with both human and nonhuman actors). New developments are coming from various form of postnormal science, strong structuration theory (SST), the sociology of scientific knowledge (SSK) or actor–network theory, postphenomenology, posthumanism, postnature theory, and nonrepresentational theory, all of which influence heritage studies and research around the world today. Thus the most interesting work in heritage research for the future reflects this bridging between the social and the natural sciences (Castree 2005) by stressing human relations with nature and how human beings make sense of nature. This implies

that the transformation of heritage into a vital resource for society requires an understanding of the relationship between nature and society as a power relationship.

The questioning of the Cartesian dualism that led to the division between nature and culture, body and mind, and so on has also led to new discussions concerning another problematic topic in heritage and society, namely the relationship between tangible and intangible heritage. Heritage has both tangible and intangible aspects, which often represents a problem for heritage research and management. In one sense, heritage consists of material or tangible culture, and all the ways human beings are related to their material and physical surroundings through cultural landscapes, objects, artifacts, places, and spaces. In another sense, heritage has intangible aspects through the immaterial manifestations of society over time (living cultures). Now this requires seeing the tangible and the intangible as co-implicated, so that it is impossible to study them in isolation.

To conclude, the relationship between heritage and society can be viewed in narrow or broader terms. Heritage can be a topic complex and wide enough to include everything; it can be as wide as a landscape, since it reflects the way humans have cared for, built in, and exploited their surroundings over time. From a critical perspective, it is important to acknowledge that heritage is social and represents sites of struggle; thus it reflects how society is stratified and differentiated—which means that the question of what heritage is will have as many answers as there are social groups, classes, nations, and identities around the world.

SEE ALSO: Authorized Heritage Discourse; Faro Convention; Heritage and Landscapes; Heritage and Politics; Heritage and Sustainability

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Heritage and Sustainability

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Against the increasing environmental, economic, and social crisis that our societies are facing worldwide, various approaches to foster sustainability are currently being investigated and heritage seems to be taking a significant place among them. Heritage is obviously part of culture. It supports and transmits culture and at the same time it is a socially constructed object. In recent years, scholars and policy makers have analyzed the relation between sustainable development (SD) and culture, considering culture in its different meanings (heritage, landscape, arts, traditions, ways of life) and underlining both the advantages and the risks of this growing relationship (Auclair 2014). This articulation can give opportunities to many practitioners, in the arts and the culture sectors on one side and in the SD sector on the other, to reflect on their own actions, modify their practices, and develop new partnerships.

Nevertheless, limits come from the focus put on market-oriented culture and on heritage strategies, and from forms of instrumentalizing culture. Although many actors are still battling to integrate culture into the national and local agendas, notably due to a general decrease in public funding, culture is nowadays frequently acknowledged as a component of sustainability, either as the fourth pillar of SD or as a transversal or a fundamental dimension of it. A number of major cities throughout the world (e.g., Lille, Barcelona, Belo Horizonte, Bogota, Malmö, Milan) have adopted Agenda 21 for Culture, which was defined in 2004 by the United Cities and Local Governments (UCLG) association in order to establish links between culture and SD policies. More recently, during the UCLG Culture Summit that took place in 2015 in Bilbao, “cultural heritage as a driver of sustainability”

was emphasized. The theme of UNESCO’s 2013 Congress in Hangzhou (China) was “Culture: Key to Sustainable Development,” and its concluding statement strongly acknowledged culture as a central element of sustainability. Many academic works have explored under what conditions culture and heritage-based actions can contribute to sustainable territories (cities as well as rural areas) and improve the living conditions of the population (Auclair and Fairclough 2015; Dessein, Battaglini, and Horlings 2015; Hristova, Dragičević Šešić, and Duxbury 2015). However, criticism has been raised in recent years against the notion of SD, by underlining the limits of the concept; the single word sustainability seems nowadays to be preferable, and the idea of cultural sustainability has been explored and outlined as a fruitful concept (Dessein, Soini, et al. 2015). New theoretical models are emerging and innovative practices for sustainability are being tested by international and national bodies as well as by local actors, civil society, and the citizens themselves. Most of these theoretical and practical developments aim at establishing citizens as key actors and agents of change.

In order to reveal the growing relationship between heritage and sustainability, the recent evolutions of these two concepts will first be highlighted. This will be followed by an analysis of three main cross-cutting issues: heritage as place-based approaches, heritage as people-centered processes, and heritage as local democracy practices. To conclude, some alternative theoretical and practical pathways will be highlighted.

Sustainability and heritage: two major challenges for the twenty-first century

Definitions, perceptions, and representations of both sustainability and heritage are constantly evolving. Criticisms of the concept of SD have increased, pointing notably to the fact that this concept is embedded in a neoliberal economic model and is based on the dogma of unending

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growth; hence the predominant weight of economic and financial interests makes the three pillars system of SD (economy, environment, social) quite problematic. There seems indeed to be a growing tension in our societies between two driving forces: on one hand, a prosaic approach, based on pragmatic, technical, and materialistic values; on the other, a poetic approach, based on sensitive, symbolic, and spiritual values (Morin 2007). It appears that, despite a number of international summits, nation states seem unable to take common decisions to prevent the aggravation of social exclusion and inequalities inside as well as between countries, or the increase of climatic changes and environmental degradation. Many works demonstrate that there cannot be infinite growth on a planet with limited physical and geological resources. Economists such as Serge Latouche (2007) have investigated new models of society without growth. Alternative theories, models, and practices for sustainability and social well-being have therefore emerged, founded on the notions of “degrowth,” “slow” attitudes, “transition” initiatives, and on the spreading concept of a “commons.” In addition, economic and financial criteria such as gross domestic product (GDP), used for comparing economic progress and defining levels of wealth, are nowadays subject to critical debate. GDP essentially measures market-oriented activities and monetary exchanges, and scholars, civil society organizations, and local governments are therefore currently conducting theoretical and practical work to define other indicators, which are not based on competition, performance and profit making. The aim is to identify values for the well-being of present and future generations and to establish new models of sustainability on the basis of people-centered approaches and qualitative criteria, notably cultural indicators. These theories connect with social and political movements (Antiglobalization, Occupy, Indignados, Places, Global Justice, Buen Vivir) that have arisen recently in various countries in the world and the fight for social justice, local democracy, and greater environmental awareness being supported by local actors in the civil society.

All these ideas and movements raise a series of issues related to our fundamental needs and expectations. What are our present needs? What kind of society do we wish to leave behind for the

next generations? What can be the role of culture and heritage? What have we inherited from the past, and what will we be able to transmit onward? What are the relevant tools for defining, preserving, and creating our cultural resources? Who has the legitimacy to drive culture- and heritage-based actions? What should the role of the citizens be? These crucial questions contribute to explaining why heritage has become a major dimension of sustainability, as an issue not only of preservation but also of creation, adaptation, and resilience to changes (Auclair and Fairclough 2015).

The notion of heritage has undergone noteworthy modifications in the past decades. Heritage is no longer considered a collection of objects and sites to identify, conserve, and protect, taken charge of solely by “experts,” but it is seen as a place-based, people-centered process that articulates key values of history and memory, identity and place, democracy and citizenship. These approaches are inserted in a number of international documents: the Florence European Landscape Convention held in 2000 (visit <https://rm.coe.int/1680080621>), the Faro Convention on the Value of Cultural Heritage for Society held in 2005 (visit <https://rm.coe.int/1680083746>), the UNESCO 2005 Convention on the Protection and promotion of the Diversity of Cultural Expressions, the UNESCO 1972 and 2003 Conventions on tangible and intangible heritage, and the UNESCO 2011 Recommendation on Historical Urban Landscapes. Most of these texts insist on broadening the concept of heritage, on taking into account tangible and intangible heritage, arts, customs, and behaviors as well as natural elements, objects, and buildings, and on developing inhabitants’ participation. This means acknowledging the diversity and plurality of individual and collective identities and encouraging dialogue and exchanges between generations, between neighborhoods, and between communities in order to promote sustainable territories.

Heritage as a place-based approach

From the start, sustainable development was embedded in a framework that links the local and the global levels (“think global—act local” was

one of the SD principles). However, there seems to be a current shift in SD's theoretical setting (as well as in that of many other policies), characterized by growing emphasis on the local level, which is seen as the basis for alternative ideas and solutions and as the most efficient level for action (Auclair 2011). According to the specificity of the context, the term "local" can relate to a community, a neighborhood, a village, a town, a region, and so on. The term "relocalization" is frequently used in expressing this turn and in developing place-based, transversal approaches to local activities. The objective is to put into practice bottom-up methodologies that are based on the participation of the population and of local actors. Facing the limits and risks related to globalization (homogenizing influences and destruction of traditional cultures, threats on the viability of locally made products, and marginalization of certain territories and countries), the aim is to promote values of "localness."

At the same time, attention is given to enhancing the connections with other communities and the links with other territories, in order to prevent identitarian closure and its dangers of fundamentalism and extremism. Heritage as a driver for sustainability means encapsulating heritage into wider policies, linking it with culture, education, social action, health, ecology, city planning, and so on. Although heritage is commonly seen as a tool for local development, particularly through tourism, many works emphasize the social aspects of heritage, and not only its economic benefits for the territories. One of the problems seems linked to targeting for support only those cultural and heritage policies that provide economic or communication benefits. In the growing competition between cities and between regions, local politicians are undeniably looking for strategies that should be economically profitable and efficient in terms of territorial marketing and branding. Considering heritage as an essential resource for local communities presupposes adopting a large definition of this notion, one that encompasses urban, industrial, and rural sites and landscapes, together with traditions, languages, and crafts. It also means acknowledging and articulating national, local, and indigenous cultures and taking into account world heritage sites, national heritage, as well as ordinary, everyday heritage. The issue is to recognize the heritage of "home,"

and not only that of the "holidays." The challenge is indeed to balance two strategies, which can appear complementary or conflicting: on the one hand, heritage for tourists and visitors; on the other, heritage for the local population.

Heritage as a people-centered process

By identifying what counts and what makes sense for the inhabitants, heritage-based strategies renew principles and methodologies applied to local development. The Faro Convention appears to be a key factor in this approach of linking heritage and sustainability, as it puts first people's values, aspirations, and needs and promotes the diversity and plurality of their views and values. It explicitly mentions everyday, ordinary living heritage as a noteworthy category—and not only the historical, aesthetical, and remarkable elements identified by "experts." Heritage as a lever of sustainability means supporting local strategies that incorporate emotions and attachment to one's living place. It supposes moving beyond profit-driven approaches, which tend to use heritage only as a tool for the embellishment of cities or as an instrument for economic development. The aim is to preserve heritage not for its own sake, but for explicit and broad social benefit (Fairclough et al. 2015). The values of heritage-based actions for people and communities are plentiful: heritage can contribute to enhancing local identities and places of belonging, to encouraging cultural diversity and intercultural dialogue, to fostering access to culture, and to developing cultural rights and human rights. The aim is to increase social inclusion, equality, equity, and fairness. The Faro Convention also insisted on increasing the role of citizens in defining, deciding, and managing their cultural environment. Besides, in the words of the convention, "everyone, alone or collectively, has the responsibility to respect the cultural heritage of others as much as their own heritage" (Article 4b). Responsibility was defined by the German philosopher Hans Jonas as a moral principle and as a major component of SD (Jonas 1984); he was indeed concerned about social and ethical issues, and part of his work focused on the future of the planet and on the conditions of human

survival. Jonas showed the responsibility we collectively have toward the present generations, but also toward future generations. Responsibility and rights appear as fundamental standards in heritage policies and practices. However, responsibility for heritage cannot be the exclusive domain of experts or public authorities. It introduces new governance strategies and tools, and supposes democratic participation designed “to involve everyone in society in the ongoing process of defining and managing cultural heritage” (Preamble to the Faro Conference; for both quotations, see <https://rm.coe.int/1680083746>).

Heritage as local democracy

Heritage, seen as a place-based, people-centered strategy for sustainable territories, leads to inventing new governance tools and original participatory methods for the co-construction of policies and actions based on values of sharing, exchanging, and co-deciding. However, while there seems to be a certain consensus among scholars and professionals to consider heritage as a fundamental resource for societies, this statement can lead to different levels of democratic engagements and practices. Linking heritage and sustainability supposes places and communities that are involved in heritage issues and in the preservation and valorization of heritage. Various activities are proposed, such as conferences and debates, pedagogical events for younger children, participatory exhibitions focusing on ordinary, everyday heritage, or “urban walks” involving inhabitants as local guides. These actions contribute to the inhabitants’ greater acquaintance with the different neighborhoods of the city and better understanding of them; consequently they can foster citizenship by changing representations and by stimulating pride in or attachment to the place where people live. Hence, implementing innovative governance methodologies for heritage management implies often quite significant changes: it means redefining the roles of the different actors involved—state, local governments, private stakeholders, civil society, and inhabitants. The challenge is to stimulate the values of local democracy among all the stakeholders. Promoting empowerment and developing capabilities, for

example, can be used as means to encourage participation. Governance methods linking experts, public authorities, and inhabitants can help them to reach successful levels of co-responsibility and co-construction. Besides, considering heritage not as a collection of objects but as a whole process that encompasses past and future requires adequate changes in policies in order to articulate short- and long-term perspectives. This leads to implementing governance strategies and tools for preserving and safeguarding heritage, but also for supporting changes, transformation, and adaptation. The recurrent use of the prefix “post” (e.g., postmodern, postindustrial, postcolonial, post-carbon) illustrates the doubts and questions we have about the future of our societies, the “after” being often seen as worse and less sustainable than the “before.” So, in these times of uncertainty, the fundamental challenges for heritage, considered as a means to enhance the link between past and future, is to support human dignity, emancipation, well-being, freedom, and peace.

Investigating alternative pathways

Heritage is widely acknowledged as an essential dimension for every community or society, and it can be found at the core of many ongoing issues. Indeed, in a context of intense competition between territories, a major challenge is to limit the instrumentalization of heritage in mere territorial branding and economy-based issues and to support policies and activities that sustain individual and collective well-being. While many alternative theories and practices are currently developing among scholars, social movements, and grassroot initiatives, the two related concepts of degrowth and the commons are gaining an increasing audience: these notions seem to be establishing a new framework for dealing with heritage issues.

Although the term degrowth can still appear provocative in times of massive unemployment and social exclusion in the global North and of considerable poverty in the global South, it relates to a model that fosters environment preservation, promotes conviviality, social justice, and democracy, and enhances the values of localness. Likewise, the spreading concept of

the commons is a consistent tool for preserving vital resources such as natural ones—but also knowledge, culture, tangible and intangible heritage—and for supporting collective responsibility and self-organization. The purpose is to limit enclosure, privatization, and the exploitation of essential resources. So, between market-oriented strategies focused on consumerism and economic growth at one end and centralized top-down public policies at the other, the commons approach appears as a third path for setting citizens as key actors in all these changes. The commons exist when people—forming a community—identify and define a resource as a common, when they decide, together, to take charge of this resource, which they consider fundamental, and when they establish collective rules and practices for a fair, ecological, and democratic use of it. Hence commons are not solely elements such as forests, or heritage “objects” that need to be protected and conserved; they suppose a process based on participation, transparency, and equity. So, considering heritage as a common means taking into account the cultural needs and aspirations of the inhabitants for mutual social benefit. However, this shift in heritage paradigms appears in many cases as an ongoing process. Indeed, it relates to a theoretical and practical turn, which implies new ways of considering and defining heritage and supposes alternative governance tools and methods. These changes will take time.

SEE ALSO: Community Heritage; Experts and Stakeholders; Faro Convention; Heritage and Policy; Heritage and Society

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FURTHER READINGS

Heritage and Value-Based Approach

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That society will seek to conserve only that which it values is a truism underpinning a value-based approach to heritage. Values are taken to represent the social association of positive qualities and characteristics with things rather than relate to the realm of ethics and morals that guide human behavior, although it is understood that the values people hold also influence the values they assign to the physical world. The sum of the values perceived in a particular place or category of heritage coalesce to represent its cultural significance, typically summarized in a statement of significance, and it is this significance that a value-based approach ultimately seeks to conserve (see VALUE OR SIGNIFICANCE). The categories of heritage over which a value-based approach is applied have expanded considerably in recent decades to embrace, inter alia, museum collections, modern art, archaeological objects and sites, historic buildings and areas, and urban and rural landscapes. Thus this approach has become the dominant guiding framework in identification, documentation, interpretation, and various other facets of the decision-making process over heritage in the early twenty-first century.

The attribution of values to the material remains of the past existed well before a value-based approach assumed center stage in heritage management. Indeed, Alois Riegl, a professor of art history at the University of Vienna and general conservator in the Austrian state, articulated what is widely acknowledged as the first typology of heritage values in his 1903 pamphlet *The Modern Cult of Monuments: Its Character and Origin*. In this essay, Riegl sought to classify the constituent values associated with the concept of the monument (broadly defined) by subdividing them into what he termed “present-day values,” such as use and newness,

and “past values,” for example commemorative, historical, and age values. His conceptual insights were intended for practical application in the elaboration of a national system for conservation. Moreover, Riegl anticipated several critical concerns that would later occupy the international conservation movement, recognizing the multiplicity of values potentially associated with heritage and partially illuminating the contradictions and conflict inherent in adopting such an approach. For instance, a structured opposition exists between present-day and past values, age value ultimately depending on a contrast with the new and the modern. However, notable silences are also apparent in Riegl’s scheme, particularly concerning the role of the public in attributing values and the interplay between expert and lay knowledge. These, too, would come to greater prominence in the late twentieth century.

The most significant contemporaneous influence on the emergence of a value-based approach is the Australian Committee of the International Council on Monuments and Sites’ (ICOMOS) Charter for Places of Cultural Significance (the Burra Charter). The charter was first published in 1979 with the intention of providing guidance and establishing standards of practice for those responsible for places of cultural significance in Australia, and was subsequently reissued under various iterations up to the most recent version in 2013. In particular, it defined and popularized the term “cultural significance” as designating the combined aesthetic, historical, scientific, and social values of a place, although significance evidently has a longer genealogy of usage in the United States (Samuels 2008). A key motivational influence behind the creation of this charter was the perceived inappropriateness of applying western (particularly European) approaches to heritage management, as exemplified by the influential 1964 International Charter for the Conservation and Restoration of Monuments and Sites (the Venice Charter), to Aboriginal, indigenous, and nonwestern contexts (see HERITAGE: NONWESTERN UNDERSTANDINGS). In short, the central assertion of the intrinsic qualities of

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material fabric is problematic when considering places of significance for cultures that may not produce monumental buildings and where oral traditions, knowledge, and social practices are more reflective of an intangible cultural heritage. By implication, new mechanisms were required to broaden the range of stakeholders and values involved in the conservation and management of such places.

Further impetus toward the adoption of a value-based approach came from the Los Angeles-based Getty Conservation Institute, whose research and advocacy from the 1990s stimulated the worldwide export of the principles emanating from the Burra Charter. The work of the Getty Institute manifested itself in a series of reports exploring the role of heritage values and conservation in a rapidly changing world. A primary focus was on elaborating methodologies for assessing cultural significance and for disseminating learning with partner organizations from the practical application of the approach to geographically diverse contexts and to different categories of heritage (see, e.g., de la Torre 2005). The rhetoric of high-level international discussions and their published proceedings increasingly revolved around more pluralistic interpretations of heritage and critical concepts such as authenticity, best exemplified by ICOMOS's influential 1994 Nara Document on Authenticity. By the start of the new millennium, values and cultural significance were in the foreground of conservation charters and conventions, most particularly the Council of Europe's 2005 Framework Convention on the Value of Cultural Heritage for Society (the Faro Convention), which essentially places people and human values rather than material fabric at the center of cultural heritage (see FARO CONVENTION). In parallel, and in response to these developments, the policies and practices of many national conservation agencies around the world were also changing to reflect the growing emphasis on values, significance, and public participation.

The integration of a value-based approach into the thinking of heritage agencies stems from the premise that this kind of approach results in better decisions and outcomes for heritage, predicated on the notion that understanding why something is important, how, and for whom is a necessary first step in effective

conservation. For proponents, the approach is asserted to facilitate a more democratic and comprehensive attitude to heritage management, given its emergence from a recognition of the multiplicity of ways—including contradictory and contested ones—in which different people and groups value heritage differently over time. Values and meanings are explicit rather than implicit. Thus a value-based approach has the capacity to improve participation by opening up conservation processes to greater scrutiny and public accountability, while also encouraging the continuous engagement of heritage professionals in self-reflective practice. Further ascribed benefits concern its flexibility of application, at various spatial scales (ranging from an individual object to a landscape) and to diverse aspects of the management process, from the identification of something as heritage to its conservation, use, and interpretation. Finally, the language of values and significance arguably provides a unifying framework that binds disparate heritage disciplines, practices, and communities of interest around the world via common reference points.

Value typologies are a key device in the application of a value-based approach; they consist of simple lists of values commonly associated with heritage and used in formal designatory processes and assessments of significance for conservation management plans. As this approach has gained greater currency in recent decades, the number of published typologies has proliferated, emanating from international and national heritage agencies, professional institutes, heritage practitioners, and academia. Widely cited typologies include those by Australia ICOMOS (1979), Lipe (1984), Feilden (2003), and English Heritage (2008; for a tabulated overview of value typologies, see Fredheim and Khalaf 2016). The expanded range of values that certain later typologies contain reflects the emergence of contemporary socioeconomic value sets designed to supplement those traditionally attributed to heritage, such as historical and aesthetic interest. Furthermore, nuances are evident in the multivariate ways in which the same or similar values are expressed; these differ according to the professional or disciplinary backgrounds of the author, the categories of heritage predominantly operated with, and the geographic focus of the elaborated typology. Typologies are criticized for their reductionist

potential, sometimes static nature, and inability to capture the full range of values attributed to heritage. On the other hand, they also provide flexible frameworks that can assist in a range of heritage management processes.

However, the worldwide expansion of a value-based approach and its encompassing of a broader range of heritage categories have not proceeded without critical reflection. Indeed, its emergence was in part a response to debates over whose heritage is being conserved, by whom, and for what purposes; and this approach, too, continues to be problematized within enquiries that critically examine the universal applicability of heritage values, practices, and ethics. For example, at the global scale, the sustained criticisms over the substantial imbalance of the sites inscribed on the World Heritage List by UNESCO as representing a monumental and tangible European heritage is illustrative of these debates. Additional philosophical and practical issues are apparent in the implementation of a value-based approach, not least the slippery concept of value itself. Whereas the dominant interpretation of heritage values in the humanities and social sciences is that they are mutable social constructs attributed by people, the belief in the intrinsic value of material fabric lingers for many in practice. This goes some way to explaining the apparent gap behind the rhetoric of a value-based approach and its variable implementation on the ground.

Several intersecting tensions underline some of the ongoing implementation challenges. First, the integration of economic considerations into value-based assessments is problematic. Fundamentally, this may be construed by some as demeaning of the “pricelessness” and intrinsic worth of heritage (Mason 2008). Although the concept of value is central to economics and cultural values, economic thinking typically reduces things to a quantifiable price determined by the market, whereas cultural values are plural in their construction, representing multiple meanings attributed by different groups and individuals in visual, textual, and other non-numerical ways. Thus the weighting afforded to economic values in comparison with cultural values and how the two are integrated into balanced decision-making processes over heritage are critically important matters if economic values are not to marginalize other types of value. Potential clashes of value

are most prevalent in the area of urban heritage, where redevelopment pressures are usually greatest. However, the economic importance of the global tourism industry also shapes the ways in which archaeological and other sites are exploited for economic ends, the attraction of international tourists being frequently privileged over the needs of indigenous populations and heritage, as Samuels (2008) illustrates in the case of Tunisia (see *ARCHAEOLOGY AND TOURISM*). In the context of scarce financial resourcing and political pressure to justify conservation through the promotion of its instrumental benefits, economic values will remain center stage for heritage.

A second tension relates to the involvement of the public and the concept of social values, taken to represent collective attachments to place and the associated meanings or values important to a community or communities (Jones 2017). This constitutes a particularly important consideration, given the aspirations of a value-based approach toward greater inclusivity. That heritage remains a primary domain of the expert is a prominent contemporary critique, particularly as it contributes to the propagation of what Smith (2006) terms an authorized heritage discourse (AHD), whereby certain values and ways of working are privileged and sustained through professional knowledge (see *AUTHORIZED HERITAGE DISCOURSE*). By way of mitigation, the Burra Charter and national heritage agency guidelines in jurisdictions such as England seek to position social and communal values on the same theoretical plane as historical, aesthetic, and evidential value. However, their integration has proven more difficult to achieve in practice, and social and communal values are often underrepresented or marginalized within designation, management, and conservation processes for a complexity of reasons, including embedded institutional cultures and policy-maker concerns over their transient nature (Jones 2017). Achieving a more representative heritage and promoting its sustainable stewardship with the community may be difficult to bring about until such values are given due regard.

Several alternative approaches advocating a “living heritage” and a “narrative-based” conservation philosophy have been articulated by those who are critical of a value-based approach (Poulios 2010; Walter 2014). These

analyses share a fundamental concern with the philosophical underpinnings of a value-based approach, which is argued to remain rooted within a nineteenth-century western conservation paradigm, thereby ensuring a continued focus on the material authenticity of fabric and on the dominance of professional expertise. Such privileging of physical fabric, they argue, creates a sense of discontinuity between the past and the present-future, effectively rendering the material world static (Poulios 2010; Walter 2014). However, neither of these alternatives are sufficiently well developed to supplant a value-based approach, particularly in its application to a broad range of heritage categories, nor do they yet provide a realistic means for day-to-day heritage management and decision making. Indeed, a living heritage approach applies largely to living heritage sites, loosely defined as those that maintain their original function, traditional mechanisms, and practices of ownership and management, as well as the continued presence of their sites' historical community (Poulios 2010). Consequently, examples include those sites that retain a religious function or where customary laws, traditional practices, and myths continue to operate. The question of authority over conservation decision making also persists with these alternative approaches. Nonetheless, they raise pertinent questions, not least by exposing universalizing tendencies while pointing toward the application of a pragmatic, situated ethics approach to the differing circumstances of diverse forms of heritage.

Other critiques seek to strengthen the conceptual foundations of a value-based approach and to improve aspects of its practical application. For example, Fredheim and Khalaf (2016) propose a typological framework for "holistic" value-based approaches that involve a three-stage assessment of significance, which consists of the identification of features of significance (what the heritage in question is), aspects of value (why it is valuable) and qualifiers of value (how valuable it is). The first stage is concerned with both tangible and intangibles attributes, while the third is where issues of value conflicts and prioritization are most likely to play out. Importantly, Fredheim and Khalaf recognize the mutability of values and the intergenerational changes that may inevitably occur in how people value the same thing over

time. This not only implies the necessity for periodic or cyclical reviews of significance, but also raises for future generations the vexed question of letting go of some aspects of the present heritage in light of changing values and new conservation challenges such as those presented by climate change. After all, destruction is also a judgment of value, and using the language of values and significance to determine a way of expressing the attribution of nonpositive value is, arguably, a necessary task (McClelland et al. 2013). Although aversion to the loss of heritage is a central organizing impulse for the conservation movement, such traditional orthodoxies are undergoing challenge in theory and practice.

Valuable future directions in research theory and methodology concerning a value-based approach will conceivably focus on the application of new methods and approaches to improving public engagement with heritage. In particular, social research and ethnographic methods, such as focus groups, qualitative interviews, participant observation, and oral histories offer appropriate means of divining the social values attributed by communities, while taking into account the fluid process of valuing heritage (Jones 2017). The use of digital technologies and tools will also likely be important in this regard, offering new ways for the public to interact with heritage and to capture, visualize, and integrate the multiple aspects under which it is valued. Furthermore, these new methods and approaches will potentially intersect with community-led, collaborative, and coproduction initiatives, involving, but not necessarily being controlled by, heritage professionals and agencies. Of course, realizing such methodological strategies in practice will present many challenges, including the lack of knowledge of social research skills in heritage agencies and other resource deficiencies that may undermine the capacity to sustain ongoing and dynamic relationships with the public.

SEE ALSO: Community Heritage; Conservation Plans; Cultural Resources Management; Designing and Co-Creating Heritage; Experts and Stakeholders; Heritage and Policy; Heritage and Society; Heritage Ethics;

Heritage Interpretation; Heritage Management;
Plurality and Multivocality

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Heritage Business and Marketing

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Over roughly the last 40 years—one generation of professional practice—archaeological practice globally has become part of the private sector both in large and in small countries. The rate of privatization has varied by country, but the trajectory is clear: state- and benefactor-sponsored archaeological work through direct funding and grants (which dominated the nineteenth century and the first half of the twentieth) is a shrinking component of archaeology. Thus, while archaeologists continue to be driven altruistically by professional values such as preservation, research, and education, the ability to be successful in realizing these values now requires competency in business and marketing. Archaeological charities and nonprofits must be financially viable if they are to achieve their missions, and for-profit firms must return shareholder value. Any inability of heritage organizations to meet their business requirements jeopardizes their archaeological objectives.

Research into archaeology's private sector requires use of disparate and uneven data. Some parts of the world, such as the United Kingdom and the European Union, have robust data on private archaeological practice. In 2015 the United Kingdom had an industry size of approximately US\$218 million (Hook et al. 2016; Aitchison 2015). In North America, Canada currently has an archaeological market of approximately US\$66 million and the United States one of US\$921 million (Heritage Business International 2016). Mexico has no private sector and the government is the major provider of archaeological services. Were archaeology to be privatized in Mexico, it could have an annual size of approximately US\$67 million (Dore 2016).

Throughout South and Central America, contract archaeology is the norm, too. In 2013 the Society for American Archaeology's Committee on the Americas presented research that identified that, across 18 countries, 73 percent of professional archaeologists worked in contract archaeology, the remainder working in academia. By contrast, the well-developed sector of applied archaeology in Japan is typically delivered through not-for-profit associations linked to local municipalities (Okamura 2014).

In Europe, delivery of archaeological services by private companies has become the norm since 1990 in western and northwestern countries (Ireland, Spain, Portugal, the Netherlands), but elsewhere significant state-provided services continue to exist. In central and eastern European countries, private company activity is still regulated by centralized authorities such as academies of sciences. In France there is nominally a level of competition between companies and locally based not-for-profit organizations (*sociétés anonymes* and *collectivités territoriales*), but the overwhelming majority of archaeological compliance work is undertaken by the Institut National de Recherches Archéologiques Préventives, a nominally autonomous body under the control of the French government.

Comparing the overall size of the archaeological market with traditional research funding from government and private foundations illustrates the changes of the past decades. The total value of all grants for archaeological research at UK universities in 2014–15 was approximately US\$30 million (calculated from Technopolis 2017: 39), less than one seventh of the total value of the United Kingdom's private sector archaeological market. In Canada, traditional research grants have averaged about US\$1.5 million annually over the past 15 years, only about 2 percent of the total Canadian archaeological spending. In the United States the percentage is about the same: traditional research funding is approximately US\$25 million (Altschul and Patterson 2010), about 3 percent of the total US archaeological market.

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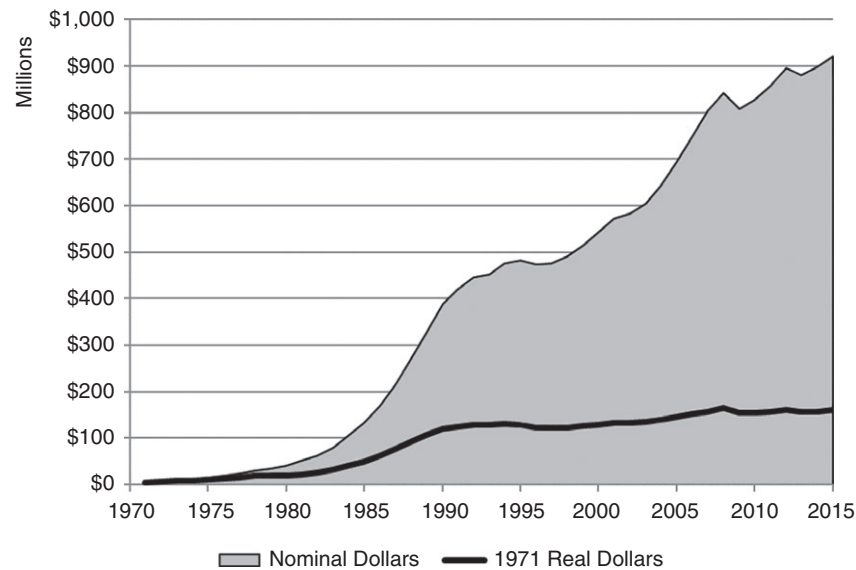


Figure 1 Real and nominal growth of the US Heritage Compliance Sector: 1971–2015.
Source: Used with permission of Heritage Business International, L3C.

Furthermore, while research funding in both Canada and the United States has remained roughly static, overall archaeological spending continues to grow. Figure 1 provides, as an example of the growth of the private sector, annual archaeological spending in the United States since 1971.

Heritage business is not limited to archaeology, although archaeology is the focus here. Six segments of the heritage industry have been defined. Archaeologists are primarily employed in the heritage compliance sector, but can be found across all sectors. This sector covers consulting work done by cultural resource management firms for environmental compliance. Multidisciplinary environmental and engineering firms perform significant portions of work in this sector and, in recent years, have been gaining market share from dedicated cultural resource firms. The heritage tourism sector offers travel and travel-related tourism to heritage resources, areas, and attractions. The heritage media sector consists of magazines, television, software, and books focused predominantly on heritage and heritage content. The heritage research, preservation, and education sector consists of organizations focused on conducting heritage research, student and professional training, and preservation activities; it

includes colleges and universities, repositories, and nonprofits focused on public education, preservation, and research. The heritage attractions sector deals with the management and operation of specific heritage attractions, for example museums. The heritage design and construction sector is made up of architectural, planning, and construction firms that specialize in the renovation, restoration, and preservation of heritage resources.

Funding for commercial archaeological work comes primarily from government or privately funded construction, extraction, or infrastructure projects as part of an environmental, heritage (see ASSESSMENT: HERITAGE IMPACT (HIA)), or social-impact assessment process. Thus money flows from the project sponsor to the archaeologist. Sometimes the funding is direct, but more often there is a chain of agencies or companies between the sponsor and the archaeologist. Typically, archaeological contracting is done in business-to-business (B2B) or government-to-business contractual relationships and falls into the general business category of professional services. While commercial archaeological contracting is generally a service, clients of archaeologists often think they are purchasing a product, because what is

delivered to them is a report—and this is also what they need to present to regulators in order to receive permits for their projects. Archaeologists often have very specialized skills and expertise in types of analyses and archaeological sciences (see *ARCHAEOLOGICAL SCIENCES*). These archaeologists may be found working for other archaeologists, providing their specialized services in B2B relationships.

Education

Many archaeologists believe that the heritage industry is unique and that this somehow means that general business principles therefore do not apply. In fact, archaeological consulting firms are almost identical to other professional services companies, and it is very difficult for the heritage industry to increase productivity levels, particularly in labor-intense compliance work. Some archaeological practitioners have formal business training and degrees, but most of them do not. Catering to the perception that heritage business is different, a few educational institutions are now offering business training expressly applied to the heritage industry. A few examples are Jiwaji University in India, which offers an MBA in heritage tourism management, Edinburgh Napier University in the United Kingdom, which offers an MSc in heritage and cultural tourism management, Simon Fraser University in Canada, which offers a professional master's degree in heritage resource management with 25 percent business content, Universitat de Barcelona, which offers a doctoral degree in the management of culture and heritage with business and economics content), and the American University of Rome, which offers an MA in sustainable cultural heritage with business and economics content. Additionally, some not-for-profit, low-profit, and for-profit organizations also offer business classes and programs that target working professionals in the heritage industry. Heritage Business International, L3C is an example of a low-profit firm that includes business education for heritage professionals in its mission.

There are also business trade organizations that specifically target archaeological and heritage consulting firms, mostly in the compliance

sector. Members of these organizations are firms, not individuals. In the United Kingdom, the Federation of Archaeological Managers and Employers provides business data and best practices for its members and advocates policy. In the United States, the American Cultural Resources Association performs similar business support and education functions for its members.

State of the industry

The private archaeology industry in the United States essentially began with the passing of the National Historic Preservation Act in 1966. At that time, most archaeologists were employed in academic institutions, museums, and federal government bodies (primarily the National Park Service). While the law was passed in 1966, regulations detailing the compliance process were published only in 1974, and it was only about a decade later, as the volume of work increased, that a wave of private firms were established to meet this new demand.

As shown in Figure 1, work increased dramatically in the United States until about 1991. Average annual growth (real dollars) from 1971 to 1991 was 18.9 percent. However, the combination of a recession in 1990–1 and market saturation led to a sudden decline in industry growth. Since 1991 average annual growth has been only 1.2 percent (Heritage Business International 2016); the US industry is sizeable at just under US\$1 billion (nominal dollars), but only small increases in value are now being realized.

In the late 1970s, a little capitalization and a lot of sweat equity was all you needed to establish a successful archaeological consulting firm. Today the market is significantly more sophisticated, firms are much larger, and a high level of expertise is needed across many technical and support functions to successfully compete in the marketplace for archaeological work. Few new firms are now being established, because a high level of capitalization is needed to be successful. While the industry meets many of the requirements for attracting capital, the critical factor of value return is lacking; and this makes it difficult to adequately capitalize start-ups.

In the United Kingdom, until the 1970s, archaeological fieldwork was undertaken by academics, museums, and interested hobbyists; there were no legal obligations for compliance work to be undertaken ahead of the destruction of archaeological sites, but a level of public pressure led to the establishment of organizations dedicated to undertaking unprogrammed salvage or rescue archaeology at that time. These were not-for-profit charities established on a regional basis and funded from central government grants.

The introduction of environmental impact regulations, together with the simultaneous recognition that archaeology could be expensive, that neither national nor local government wanted to take financial responsibility for this, and that the cost could in principle be handled through the spatial planning system (a responsibility of local government), led to the publication, in 1990, of a key policy document: PPG 16 (Department of the Environment 1990). This document established the principle that, in case developers were (potentially) going to damage archaeological sites, (a) they were financially responsible for mitigating this damage, for instance by financing fieldwork; and (b) they were free to select suppliers of their own choice to do that fieldwork. PPG 16 transformed UK archaeology and led to the rapid emergence and expansion of a market for archaeological services funded mainly by private clients.

In both the United Kingdom and the United States, the original founders of the firms established in the late 1970s and early 1980s are now retiring. Most of these firms were started with sweat equity, but have acquired significant value. They must now be purchased, and their sale price reflects this value increase. Many archaeologists with a professional interest in acquiring companies cannot afford to do so owing to their historically low salaries by comparison to those of comparably trained scientists. Nonarchaeologists who may have sufficient funds for a purchase generally have little interest in acquiring an archaeological firm, do not understand the industry and how it operates, and do not see the potential for an adequate return on investment. Thus, while a buyers' market currently exists for archaeological firms, many firms for sale

are having an extremely difficult time finding a buyer.

Two business trends have characterized the industry over the past two decades (roughly, since the start of the millennium). First, there has been a shift in perspective on the part of archaeological clients. Contracted archaeological work used to be considered value-added professional services work, much like the work of other highly trained professionals, and a market premium existed for education and experience. Today, however, archaeological compliance services have changed into commodity services (commodities are things where brand doesn't matter). They have become commodities because, in a typical client's mind, all firms in the market can do an equally good job of meeting regulatory technical requirements. There are quality differences, but there is no market premium on these differences. With commodities, price converges on cost, and margins are very small. To achieve business success, commodity firms must increase their margins more than their competitors, through hyperefficient operations, and must have a very large market share. Archaeological firms have neither large market shares nor high levels of efficiency; nor do they desire to change their business model from a value-added services mode to a commodities mode. This is one reason why the industry's value growth has been so low since the 1990s.

As in the United States, archaeological practice in the United Kingdom is a commodity service supplied by organizations that want to present themselves as professional service providers—and often by organizations that want to present themselves as providing a public good. Almost all the charities that started undertaking archaeological fieldwork in the early 1970s still have significant places in the market, and their legally constrained not-for-profit model contributes greatly to the extremely low levels of margins across the sector.

Historically, until the global economic downturn that began in 2008, UK archaeological practice was also hamstrung by high barriers to exit: many organizations that were competing in the market were artificially sustained by larger parent bodies, such as universities and city and county councils, which skewed the competitive process in their favor. Very few of these survived the intense

effects that the economic changes of 2008 had on the construction industry.

The second trend is that of market share. While the nominal dollars of the US archaeology industry are increasing, firms that are archaeological-only or heritage-only firms appear to be losing market share to multidisciplinary environmental consulting firms and engineering companies. In 2011, more than twice the number of archaeologists were hired by nonheritage firms. Additionally, the marketplace is very fragmented. The largest archaeology and heritage-only firms only have about 1.5 percent market share. This drops off very quickly, too, as there are only few large firms and many small ones. Growth through increasing market share is desirable because it drives purchasing power, optimizes efficiency and cross-functional excellence, and is a fundamental way of increasing value. Greater market share also has scientific advantages and allows for a larger influence over scientific standards, increased scientific expertise, and the ability to increase capabilities and scientific services.

Marketing

Marketing archaeological services is not different from marketing any other kind of service. Having an understanding of the distinctive aspects of the industry may influence marketing strategy and tactics, but there isn't anything inherently unique to archaeological marketing. Marketing is based upon a fundamental premise that not all work is equal in value. This means that some work (e.g., jobs, clients, sectors, types of work) will, for the same amount of cost, produce higher returns. Marketing is the process of always increasing the amount of higher-value work that a firm does.

Successful marketing requires a deep understanding of archaeological clients and their needs. This understanding can be achieved at different scales of breadth and depth—and these are inversely related. Surveys of clients and potential clients can provide a large amount of data very quickly and inexpensively, but standardized surveys tend to provide the “what,” not the “why.” Focus groups provide a better balance between data quantity and quality and allow for unstructured answers, probing, and discussion.

Interviews with individual clients provide the most insightful information, but these data may not be representative and are costly to acquire in meaningful numbers.

When the needs of prospective customers have been defined, these prospects are classified into market segments, which can be ranked for value. These segments may align with client industries such as transportation, mining, energy, and so on occasion, but many client industries can be grouped into a smaller number of segments. The segments then become the relevant units for marketing activities.

The next step is “differentiation”—that is, figuring out how one's organization is different from competitors with regard to the things your sectors care about. When firms and their products or services are the same, at least in the eyes of the consumer, a commodity market exists. So, to gain more value, firms strive to differentiate themselves from one another. This differentiation, though, should produce results that are as unique as possible to each firm and that should be difficult for competitors to emulate. Most importantly, differences must relate to the things that clients care about when selecting one firm over another.

Differences, by themselves, are not the end product. Many firms offering archaeological services list all the things they do on their websites or in their advertising collateral. Most clients do not understand why these things are relevant to what they need. To contribute to the marketing effort, the differentiators need to be turned into client benefit statements. How do the firm's differences benefit the clients in a particular sector? As an example, cloud-hosted project databases across offices may be an important differentiator but, for the client, the benefit is that they can check the status of their projects instantly from any mobile device. The benefits are the things that need to be articulated and highlighted; the way they are achieved—the differentiators—is secondary. Advertising these client benefit statements follows, with the intent of attracting new clients. Of course, the benefits must be delivered if the client is to be retained beyond the first job.

SEE ALSO: Cultural Resources Management; Heritage and Economics

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Heritage Ethics

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Heritage ethics concerns both the codes and principles that frame accepted practices in the field of heritage and much broader debates and philosophical concerns around the legal, moral, and social justice implications of heritage. The rise of heritage during the twentieth century as a complex cultural and political field and its formalization and institutionalization in national and international legislation and in other forms of governance has significantly impacted understandings of archaeology as a discipline and of the “archaeological record” as an objective entity, as the study of heritage reveals that cultural values are relative and contingent. These shifts have also helped shed light on how archaeology has been shaped within particular geopolitical and historical circumstances that have influenced both its practice and theory and its interpretations and findings. At the same time, archaeological epistemologies and practices, their focus on the material, and the research potential of the material as trace and evidence, have strongly influenced modernist concepts of heritage, shaping notions of what heritage is and how it is defined in legal and public policy frameworks. Concepts of what heritage is or can be, including the related concept of “cultural property,” have also changed significantly over this period, and many see heritage as an ever-expanding field as interest in the intangible and the contemporary overturns the idea that heritage must be old and monumental.

Also critical for understanding heritage ethics in the context of this recent history is the building and continuing impact of the major historical and intellectual ruptures of the twentieth century and their social justice implications: the events of World War II and the Holocaust; critiques of colonialism and its basis in racism; post-modernism and its critiques of expertise and

of the knowledge–power nexus; the influence of feminism and the rise of environmentalism and of forms of participatory democracy; and, perhaps most importantly, the rise of indigenous and other human rights discourses and of diverse forms of activism by indigenous and First Nations peoples.

As heritage is increasingly seen around the globe as an industry and as a part of a cultural economy, albeit in distinctively different regional forms, archaeological work is more likely to be seen as belonging to this wider cultural sector, and thus archaeologists are employed in a range of different settings, for example in private sector businesses and practices, in government and nongovernment agencies and organizations, and in museums, other cultural institutions, and universities. Archaeological research may be a component of a broad range of heritage-related processes based on legislation and associated with urban, rural, and industrial development, such as cultural resource management, cultural heritage management, archaeological heritage management, commercial archaeology, public archaeology, heritage conservation/preservation, conservation science, asset management, land-use planning, cultural planning, environmental impact assessment, land rights determinations, and so on. This in turn has the effect of making archaeological research explicitly subject to bureaucratic and legislative definitions of its aims and purposes, as well as to standards of public fiscal and legal accountability. The discipline of archaeology and the way it is taught in universities has thus been influenced profoundly by the increase in the amount of archaeological work undertaken as part of these heritage-related processes. In the context of this recent history, ethical codes and debates have proliferated since the 1980s, responding not only to well-established understandings of “stewardship” or to the obligation to conserve and curate cultural material, but to these changing forms of accountability. It is now generally accepted that all archaeological research is encompassed within the broader field of heritage and is thus also embedded within these social, cultural, political,

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and ethical contexts (Ireland and Schofield 2015).

Heritage and archaeological ethics have tended to be analyzed in terms of three main types of ethical responsibilities of practitioners: stewardship responsibilities for cultural materials; professional responsibilities to the discipline and to heritage as an expert field of practice; and, finally, responsibilities to “stakeholder” communities, often understood as “nonexpert” and external to the discipline (Zimmerman, Vitelli, and Hollowell-Zimmer 2003). Thus the codes of heritage ethics associated with professional heritage protection and advocacy organizations combine modernist ideas of stewardship, academic freedom, professionalism, and disciplinarity—which go back to the nineteenth century and earlier—with more “postmodern” concerns about rights to culture and identity, recognition, and representation. Recent developments in the management of heritage, however, tend to see a move away from understanding ethics primarily in terms of these three discrete categories and toward approaches that seek to address the ethical implications of all aspects of heritage, including its history, its theory, its accepted practices, its methods, its institutions, its products, and their consumption (Meskell and Pels 2005).

A number of key debates have dominated the field of heritage ethics, expanding out from questions concerned with “who owns the past” or who has rights over particular forms of heritage to broader investigations of how disciplines were founded and shaped, attempts to understand the influence of western ontologies, epistemologies, and embedded normative conceptions of gender, class, and race, as well as more philosophical discussions of the ethics of remembering and forgetting in the aftermath of World War II and in response to the revision of colonial and imperial histories. The dimensions of heritage ethics have thus been transformed by international geopolitics and paradigm shifts around the cultural contingency of knowledge claims. Particularly significant here have been Foucauldian interrogations of the entanglement of knowledge and power, Latourian critiques of science and modernity, feminist scholarship and critiques of androcentrism, and critiques of orientalism and of colonialism adduced

more broadly from the field of postcolonial scholarship.

Colonialism’s enduring impact as a cause of contemporary social and economic inequalities gives rise to ethical debates that are perhaps dominant in archaeological and heritage research. Central here has been the treatment of humans remains, sacred artifacts, and other cultural materials accumulated by western scholars, museums, and collectors and the demands of indigenous and other colonized communities for various forms of control, return, restitution, and repatriation (Scarre and Scarre 2006). While many museums around the world have active repatriation programs as well as ethical statements and guidelines concerning these issues, this colonial legacy continues to be contentious and without a standard ethical response. The repatriation debate can clash with strongly held commitments to cultural stewardship, which remains central to concepts of the “universal museum” and world heritage—modernist concepts that continue to retain powerful currency in the community, particularly in the face of the damage or destruction of prominent heritage places and monuments in armed conflicts (Stone 2011).

Research on legacy collections, and new research involving indigenous people’s cultural heritage, human remains, and descendant communities, continues to deal with the ongoing impact of colonialism and of forms of neocolonialism; and they do so in ethical questions such as what constitutes meaningful consultation, informed consent, community control, participation, and collaboration and, more fundamentally, how to empower, recognize, and respect indigenous knowledge systems, ontologies, and axiologies. Complicating this arena even further in ethical terms, recent developments in the study of ancient DNA stimulate great community interest in questions concerning the perception of continuity between ancient and modern populations of particular regions. Concepts of race and racial classification have been reinvigorated in the public domain, in contexts that range from personal (e.g., family history and genealogical research) to national (e.g., in the rise of white supremacist organizations).

A second dominant theme in heritage ethics concerns the so-called illicit trade in antiquities and “illegally” excavated archaeological material.

The illicit antiquities trade debate encompasses a huge diversity of local specificities—from “subsistence digging,” whereby impoverished communities exploit archaeological materials as a resource to exchange for cash, to organized crime that feeds a flourishing demand for rare collectables and to war or postconflict situations in which cultural materials are made vulnerable to theft through the breakdown of law and order. Underwater cultural heritage, largely shipwreck material, constitutes a particularly contentious area of this debate, as schisms arise between the archaeologists who work toward making the sale of recovered historic shipwreck material illegal and those who salvage or excavate underwater sites in order to produce material for sale, sometimes through well-known western auction houses. The ethical debates around the trade in antiquities also brings into play the ideological commitment to a free market economy as a driver of competing ethical standards around stewardship, the authority of archaeological expertise, and the role of the universal museum, particularly as new museums develop rapidly in areas such as Asia and the Middle East, with new collecting agendas and rationales.

Cultural tourism, and the “experience economy” more generally, provide a further arena where questions of heritage ethics are constantly invoked. Many of these debates are linked to concerns around the impacts of globalization and the interaction of global concepts of heritage (particularly world heritage, as defined by UNESCO) with local values and economics (Labadi and Long 2010). The 2003 UNESCO Convention for the Safeguarding of Intangible Cultural Heritage was seen as bringing a much needed balance to the Eurocentrism of the World Heritage List; however, it is also argued to have perpetuated the divide between perceptions of the monumentality of western heritage and the impermanence of nonwestern cultural traditions (Smith and Akagawa 2009). Also, archaeology has often been used to uncover evidence of crimes against humanity or to reveal traces of tragic events such as disasters, battles, or massacres. In some cases, this leads to what has been termed “dark heritage and tourism,” raising questions about who profits from such tourism and whether such sites educate and perform important memory work or exploit forms of voyeurism (Stone and Sharpley 2008).

Tourism’s consumption of heritage places, and the narratives provided by archaeological research, also raise ethical questions around the authenticity of the outcome of heritage processes of protection, restoration, and interpretation. Where cultural practices, traditions, and activities are also consumed, both the impact of this form of commodification on often minority ethnic or cultural groups and its propensity to embed colonialist concepts of traditional or primitive cultures as well as economic disparities between the affluent, often first-world consumer and local communities continue to be key drivers for much research and activism in this field.

Ethical concerns around authenticity were central to much twentieth-century debate and to the development of heritage as a movement. Their centrality resulted in the establishment of a series of charters that articulate shared principles and standards, the best known being the The Venice Charter of 1964 (the International Charter for the Conservation and Restoration of Monuments and Sites). The conservation and restoration of heritage buildings and objects gave rise to specialized subfields of heritage and conservation ethics. This arena continues to be strongly defined by the ethic of stewardship and concerned with the objectivity or subjectivity of conservation, restoration, and preservation decisions. However, debates in conservation have also moved toward greater focus on community interests and human rights. Concerns nonetheless persist around professionalism and around the development of the particular forms of expertise required to establish the authority of heritage experts and to secure public trust in the authenticity of the outcomes of the heritage process.

Concepts of authenticity and value remain central to all forms of heritage governance, and thus to all decisions about the conservation, listing, and protection of particular heritage places and things. Such governance regimes commonly restrict forms of access, interpretation, and use of places and things that are no longer seen as compatible with the values formally endorsed as most important. This frequently gives rise to ethical concerns about how heritage is used by states and by other powerful actors to control particular narratives about the past, and how these practices and narratives can create subtle forms of invisibility around alternative versions

of the past and other cultural identities. In fact some scholars have suggested the need to redefine heritage completely, because of the way in which the heritage system is focused on determining the special significance of things to particular groups, necessarily excluding groups that do not share these values (Schofield 2014). The ethical implications of heritage governance regimes that focus on categories of value such as beauty, rarity, and the aesthetics of the patina of age rather than on understanding people's attachment to places and things create an intransigent dilemma for heritage ethics in terms of social justice. The structures of heritage management and legislation are purposefully constructed so that heritage may be assessed and prioritized by judging which items are more necessary to a community's future.

Current approaches to heritage ethics tend to see all heritage as inherently entangled with politics and economics and, more broadly, with questions of human rights. Approaches have tended to move away from conceptualizing the ethical considerations of archaeological and heritage research as specifically defined questions that are referred to at key points in designing, undertaking, and evaluating heritage work, and toward adopting an iterative, reflective process of interrogating the impacts, benefits, and implications of all research and of analyzing the ethics embedded in all the levels of theory and practice, as well as in personal allegiances and belief systems. A hallmark of contemporary heritage ethics is that modernist concepts of stewardship and expertise continue to be strongly influential and used alongside postmodern or relativist concepts, particularly as they are strategically employed to value and engender respect for indigenous and First Nations knowledge systems and cultures. In areas dealing with conflict, peace building, and postconflict reconstruction, the task of embedding a normative and shared ethics in the work of heritage institutions such as museums or in the world heritage management system continues to be seen as crucial. Recent reviews of heritage ethics in postconflict contexts discuss the need for normative ethics to help build the bonds of "thick trust" in fractured societies—for instance by bolstering museums and cultural institutions as neutral, authoritative archives, which the broader society can trust not to take sides or cover up

uncomfortable aspects of cultural heritage. Other research is more concerned with deconstructing heritage's foundational concepts (such as those of stakeholders, conservation, stewardship, and authenticity) and with understanding the ethical implications of the often "blackboxed" nature of these ideas. While current research in heritage ethics takes a variety of approaches toward how formal ethical codes and charters perpetuate forms of disciplinary and expert privilege, all attempt to engender a better understanding of the ethico-political implications of heritage and of how it may contribute to a broader social agenda. In essence, heritage ethics aims to engender reflective approaches, which continuously question current practices and provide a critique of their social justice implications.

Emerging issues and future directions for heritage ethics concern how heritage and archaeological research might respond to pressing social and environmental problems and to their links to contemporary geopolitical events and conflicts—including climate change and sea-level rise, migration, refugees, and movements based on exclusive forms of citizenship. Recent theoretical trends, for example the "ontological turn," posthumanism, and multispecies ethics, appear to have the potential to impact significantly on heritage ethics, particularly in the area of indigenous heritage, its challenges to nature–culture dichotomies, and the approach to interspecies connectedness that is emerging as a strong feature of ethical debates about the Anthropocene; at the same time, forms of iconoclasm and extremist ideologies not only draw on narratives of inequality, past injustices, and deep cultural traditions but also target for destruction the material symbols of heritage—actions that inevitably appear to draw responses centered on the need to protect and restore the cultural heritage rather than on the far more difficult challenge of restoring peace and dialogue. Similarly, far more nuanced ethical arguments and guidelines need to be developed around research into cultural and biological concepts of race and the use of DNA in linking perceived cultural groups with regions, territories, and nations.

Finally, the capacities of digital technologies—their challenge to forms of expertise and their transformation of social participation—have already generated intense discussion in the

arena of heritage and archaeology. Questions concerning digital preservation, replication, interpretation, and visualization will continue to transform not only debates in heritage ethics, but understandings of what heritage is and of how and by whom it can be experienced. Developments in digital heritage are commonly represented as driven by threats to “real” heritage—through conflict, climate change, population pressure, disaster. The concept that humanity’s heritage is a rapidly dwindling and fragile resource appears to underpin many discussions of digital heritage ethics. On the other hand, these developments can also be seen as a continuation of the long-standing tradition of using techno-scientific practices in heritage and conservation, practices that have always created ethical tensions between the purposes of “heritage” and the diverse experiences and expectations of those communities that value it.

SEE ALSO: Authorized Heritage Discourse; Community Heritage; Countermapping; Experts and Stakeholders; Faro Convention; Heritage and Community Archaeology; Heritage and Conflict Resolution; Heritage and Human Rights; Plurality and Multivocality

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Heritage Interpretation

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There has been something of a revolution in heritage interpretation over the last twenty or so years, although, like most revolutions, it remains partial and incomplete. This short entry is an attempt both to describe something of that process and to ask “where next?” for the theory and practice of this particular aspect of professional practice.

The entry draws on examples of professional practice in the United Kingdom, but it is also informed by experience elsewhere and by a clear understanding that heritage interpretation, as a set of skills and approaches, draws on multiple sources of ideas and inspiration, which are relevant in a wide range of contexts: social, economic, and geographical, and on the different forms that heritage takes from place to place and over time. The issues raised by these examples are broadly applicable: the balance between audience and story, how those stories might be best told, who does the telling. The underlying assumption is that we cannot separate these processes from the wider context in which they take place—the site *and* the society that has decided that they somehow matter. The politics of heritage interpretation are as much part of this process as the focus group that helps identify the key story, decisions about media, or the care taken to make sure that the new display is as accessible to as many people as possible. Deciding whether to create tactile labels, or an autism-friendly space as part of a new gallery, are as much political decisions as they are interpretive ones.

The survey in this entry covers the period from about 1997 to 2017. It thus starts with the election of the Labour government in the United Kingdom. The government made a number of interventions in the arts, heritage, and cultural policy. These were less radical than one may have supposed, but they did embody a shift of

emphasis. It was this government that renamed the Department for National Heritage, with all its supposedly backward looking, old-fashioned connotations, as the Department for Culture, Media, & Sport (DCMS).

A great deal has happened since then, but in terms of broad cultural policy, of which heritage forms a small part, there has been a remarkable consistency in assumptions over this 20-year period. *The Culture White Paper*, published in March 2016 by the Conservative Government led by David Cameron, embraced much of what was already familiar and much of what was already happening somewhere. The language was different, and the balance between public and private funding had changed, but some enduring sentiments were still there:

This white paper seeks to harness the nourishing effects of culture. It seeks to ignite the imaginations of young people, kindle ambition and opportunity and fuel the energy of communities. It seeks to spread the gifts of our arts, heritage and culture to more people, and communities across the country and abroad and free the creative genius that can make a better world for all. (Department for Culture, Media, & Sport and Vaizey 2016, 6)

The most obvious transformation has been a conscious and growing focus on the audience and, to a lesser extent, on the potential for wider public participation in “interpretation.” This can be seen in government policy between 1997 and 2010 and in the requirement that nationally funded organizations should broaden their appeal to nontraditional audiences. The introduction of free admission to the national museums in 2001 was part of the same line of thinking, though this was more successful at increasing the number of visits—far beyond expectations—than it was at changing the profile of museum visitors themselves. At the same time, the museum profession in particular began to develop a much stronger sense of the social role of its respective institutions, the contribution they might make to health and well-being, and, in some instances, the part that they could play on behalf of their

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communities. Much of this is now commonplace across the sector as a whole.

Behind this focus on audiences was a much deeper set of impulses that link heritage practice on the one hand, and public engagement with it on the other, to the impact of social, demographic, and cultural shifts within the wider society. From the moment Stuart Hall asked “Whose heritage?,” as long ago as 1999, the sector has had to think more carefully about the stories it tells—or invites others to tell—about one heritage asset or another, as well as about what might constitute heritage in the first place. Its response to that challenge has included some extraordinarily innovative and exciting interpretive projects. Elsewhere the sector’s response has been to continue to do much the same thing as it has always done, but with better signage (Hall 1999–2000).

The availability of different media and new technology has enabled us to create new experiences or to experience a familiar place or object in a new way. Exhibition planning and design, the architectural impact of a new visitor center, or simply rethinking the direction from which the visitor approaches a site all relate to, influence, and are influenced by the practice of heritage interpretation.

Funding and the basis on which funding is offered or sought represents another set of influences and imperatives, allied to and reinforcing the political context in which we define, manage, and interpret heritage. Audience numbers and profiles are important here too. The continuing instrumentalism of much government policy on the arts, culture, and heritage means that funding relates to what heritage can *do* rather than to what it *is*. Heritage interpretation and heritage learning are both key elements in this.

The term “heritage interpretation” is perhaps used most often in the context of “heritage sites”—archaeological, historical, or natural sites, places, or buildings. Each of these poses specific challenges and offers discrete opportunities: making sense of a building that survives only in fragments, finding ways of making a historic interior stuffed with great paintings and precious porcelain welcoming to families, balancing the cultural and environmental value of a particular location.

Interpreters work in museums and galleries too; curators interpret their collections. Placing an object in a display case is a form of

interpretation, together with the label that accompanies it and the catalogue that elucidates its meaning and significance. In a UK context, the interpretive process was often reduced to a series of decisions about media, which may or may not have related to the needs of the audience: the label and the catalogue, panels and signs, audio tours and displays. In the United States, interpretation included people too: tour guides, costumed interpreters, living history. The latter are now well-established techniques in the United Kingdom, through innovative work by organizations such as Historic Royal Palaces and through the adoption of such approaches as a means of “bringing history to life.” Interpretation, in this context, is closely linked to audience development—finding ways of appealing to new audiences—and financial sustainability—income generation through events and through activities which could extend the length of a visit to a particular site. The current interest in the use of contemporary art to interpret historic places or collections crosses the same divide. The contemporary art installation can bring another audience to the historic house; it offers a way of challenging or subverting the conventions of the museums. It can be a huge commercial success.

There have been lots of attempts at defining heritage interpretation, from Tilden Freeman’s early reflections to more recent statements and pronouncements. The Heritage Lottery Fund (HLF), a key agent of change for UK heritage practice, offers us this:

Interpretation is not just about facts and figures, it is the way in which the interest, value, significance and meaning of heritage is communicated to people. It is a learning activity which communicates the stories and ideas behind the heritage and provokes the audience to think for themselves, coming to their own understanding about what its subject means to them. (Heritage Lottery Fund 2013, 3).

As the major UK funder of capital projects for museums, heritage sites, and the natural environment, it is unsurprising that the HLF connects good practice in interpretation with the delivery of its own objectives for the initiatives it funds, be they a small, community-based archival project,

a new gallery, or the refurbishment and redisplay of a major museum. Projects are supported where they demonstrate a high probability of enabling people to “learn about heritage” and have an enjoyable experience in so doing, and where the project has the potential to encourage “more and a wider range of people to engage with heritage” (<https://www.hlf.org.uk/interpretation-guidance>). The Fund’s consistent validation of the audience and of learning as a key outcome for all the projects it funds has contributed more than anything else to the shift from media to the relationship *between* audience and media, as the hallmark of good interpretive practice.

The Association of Heritage Interpretation (AHI), a UK-based network aimed mainly at heritage professionals, for example, echoes the idea of this connection between interpretation and the audience for whom it is intended—the extent to which it can *change* how it might think or feel about a site, a collection, or an event. In 2017, its website stated:

Interpretation is primarily a communication process that helps people make sense of, and understand more about, your site, collection or event. It can ... Bring meaning to your cultural or environmental resource, enhancing visitor appreciation and promoting better understanding ... Enhance the visitor experience, resulting in longer stays and repeat visits ... Enable communities to better understand their heritage, and to express their own ideas and feelings about their home area.

The Association then goes on to quote Tilden and his definition of interpretation as an “educational activity which aims to reveal meaning and relationships through the use of original objects, by first-hand experience, and by illustrative media” (Association of Heritage Interpretation, n.d.).

Freeman Tilden published *Interpreting Our Heritage* in 1957. It is customary, though faintly alarming, to begin with him in any analysis of heritage interpretation—customary, because he is so often credited with founding the “discipline,” and alarming because we are still citing his six principles 60 years after they first appeared. The “our” of the title also raises as many questions as the text seeks to answer. These six principles are widely available online, usually detached from

the book in which they were listed. After an early career in journalism, Tilden turned his attention to the National Parks Service in North America and began developing the ideas with which he is still so closely associated. He insisted on the relationship between interpretation and the audience, that interpretation was not just a matter of conveying information, and that its primary aim was provocation, not instruction. He summed up his approach thus, quoting an unnamed ranger in the Parks Service: “Through interpretation, understanding; through understanding, appreciation; through appreciation, protection” (Tilden, 1957, 38).

English Heritage reworked this formula in the first decade of this century for the sites it managed. It imagined a “virtuous circle” of “understanding that leads to valuing, and then to caring and enjoying” the physical heritage of the castle or ruined abbey. In this instance, the unifying theme became the “story of England,” a narrative thread that united the public presentation of a diverse portfolio of some 400 or so properties. Visitors to these properties were invited to “step into England’s story” through targeted investment in the conservation and interpretation of those places where significant moments in England’s history happened (visit [step into england’s story](http://stepintoengland.org), which is part of English Heritage’s Story of England website). Already underway under its previous chief executive, this process was accelerated in 2015, when English Heritage ceased to be an agency funded by central government: it was reformed with a one-off grant of £80 million, which supported its transformation into a self-sustaining, independent charity (English Heritage, n.d.).

In this, the new English Heritage bore a passing resemblance to the National Trust, a charity since 1895 and increasingly successful as a membership organization and manager of its own portfolio of historic houses, stretches of coastline, and breathtakingly beautiful landscapes. Its own approach to interpretation was also undergoing something of a transformation at the same time. Neatly avoiding the vexed idea of a story of England—as though there could be such a thing—its interpretive principles were drawn together under the injunction to remember that “everything speaks”: “Colour schemes, smells,

what's on the menu. The style of signage, leaflets, activities, passing conversations. The position of things, parking, paths, benches, even bins. Every detail adds up to tell a property's story" (National Trust 2013).

This is a familiar basis for interpretive planning, a multidisciplinary and multidimensional approach to bringing together audience, story, and media at the right place and in the correct combination. The visitor is there implicitly, following the signs, choosing something for lunch, reading the leaflets. There is a connection between each of these elements—they mark a point on a visit, from arrival to departure—and they might share a common visual identity and be congruent either with the property or with the National Trust brand.

But there was a bigger idea at play here, underpinning these helpful interventions and interesting observations: the idea of a "spirit of place," which "defines the very essence of a property ... the one thing we want every visitor to understand and take away with them" (NT, 2013). As with HLF, AHI, and Tilden so long ago, here was the key message, the story that the visitor was not supposed to miss. To its credit, the Trust acknowledged that there would be more than one story and that visitors, in any case, came to its properties for many different reasons. But there was still, just like in the story of England, "a strong governing idea," without which "individual layers of interpretation will be no more than a collection of facts and won't add up to anything whole" (National Trust 2013). This could have been taken directly from Tilden's fifth principle: "Interpretation should aim to present a whole rather than a part."

Spirit of place can be a useful organizing principle, from which everything else can follow. The risk is an innate conservatism, a wish to preserve something that is held to be self-evidently worth preserving and that is also usefully vague and intangible. But it does not necessarily mean an absence of change, or that the moment preserved has to remain the same indefinitely. In the case of Dunham Massey, for example, shortlisted for the Museum of the Year Award in 2015, that spirit was evoked by "temporarily stripping out the traditional treasures of the house ... [to uncover] greater treasures still." As part of the Trust's commemoration of the centenary of the outbreak of

World War I, the house was redressed in its role as a hospital for wounded soldiers brought back to Cheshire in the hope that they might recover from their injuries. This "uncompromising decision," in the citation of the judges for the award, "resulted in a wonderfully moving, enlightening and wholly fitting tribute to the kindness and courage of the house's former occupants" (Hems 2015). Elsewhere the Trust has worked hard to encourage visitors to participate in the process of defining the spirit of a particular place, and has encouraged them to see it in new and sometimes unexpected ways. Where the processes of conservation and restoration would once have been hidden away behind hoarding and dustsheets, or the property itself closed to the public, visitors are now invited to look more closely at the processes involved in keeping the roof on or cleaning each tiny fragment of stained glass window. This, too, is a form of heritage interpretation, far removed from the laminated room guide or "Do not touch" signs of many historic houses.

And yet the partial revolution remains. The other significant change in heritage practice over this same period has been a widening definition of what heritage is—the "Whose heritage?" question again—and the emergence of community-based, locally driven, informal projects to define and interpret it. In this context, heritage interpretation is not simply an aspect of professional practice, a discipline with a set of conventions and expectations associated with training, skills, and possible approaches, but an activity in which everyone can take part. As a participant in the process of interpreting heritage, the public can act as author and audience at one and the same time, researching and revealing a story that matters to its members. That this is a possibility—acknowledged, if less often realized—is the most important change in the practice of heritage interpretation over the past twenty years.

SEE ALSO: Archaeology and the Present; Authorized Heritage Discourse; Heritage and Politics; Heritage and Society

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Heritage Management

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Cultural heritage management (CHM) involves those practices that identify and evaluate a community's cultural heritage resources and the programs that ensure their transmittal to the next generation. In the United States, where CHM is more commonly referred to as cultural resource management (see CULTURAL RESOURCES MANAGEMENT) (CRM), CHM operates within a system that includes government agency practitioners, private firms (mostly for profit, but some not for profit) that do much of the infield work of CHM, and the academic institutions that train the students who eventually become specialist practitioners. In other countries elements of the system may be underdeveloped, or may not even exist. For example, in some countries, CHM work is exclusively or almost exclusively carried out by the government, and the private CHM industry is underdeveloped or nonexistent. Some authors, such as Carman (2015), consider CHM to be synonymous with archaeological resource/heritage management; but in its broader application, globally, CHM deals with much more than archaeological resources under the aegis of "heritage."

For CHM practitioners, cultural heritage describes a community's assertion of rights to define who its members are and what they deem important. This heritage includes all aspects of social identity that are essential for community self-definition: places, norms, and beliefs—how members are to behave and what practices and knowledge must be passed on to future generations to ensure cultural viability. Heritage has both tangible (buildings, monuments, sites, landscapes) and intangible (social behaviors such as pilgrimage, rituals, feasts, dances, food ways) aspects. Any of these

aspects may be important in the history of a community, but they only become heritage when that community imbues them with meaning in relation to how they inform members as to how to live their lives and act toward others (Altschul 2018; see COMMUNITY HERITAGE). The Framework Convention on the Value of Cultural Heritage for Society (the Faro Convention (see FARO CONVENTION)) of 2005, which emphasizes tangible and intangible cultural heritage as valuable resources, acknowledges the diversity of these resources and stresses their significance for sustainable economic development (see HERITAGE AND SUSTAINABILITY). Following the Universal Declaration of Human Rights, the Faro Convention acknowledges that human rights include the right to cultural heritage. Cultural heritage is not a static entity but evolves as the community changes. The role of CHM experts is to work with all stakeholders in a project, from proponents and regulators to community members and other interested parties; they are not simply passive agents but critical actors in the process.

A nation's desire to preserve its heritage is almost always pitted against economic development, particularly natural resource exploitation, infrastructure improvements, and urban renewal, which in many cases results in impacting or destroying tangible heritage and in disrupting or leading to the loss of intangible heritage practices. CHM must be situated within social, political, and economic contexts, and is therefore not simply the application of laws, regulations, charters, or conventions. It must be adapted to the circumstances of a particular country, or even to a specific case. In industrial societies, regulatory frameworks exist that ostensibly balance cultural heritage and economic development. In developing countries, these frameworks either do not exist or, if they do, they are enforced inconsistently. The fact that numerous overlapping laws, regulations, conventions, and charters protecting different aspects of heritage exist should not be surprising, given the importance placed on heritage at the local, national, and international levels.

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Primary approaches to CHM

There are two primary approaches to CHM as it is practiced globally today (Altschul 2018). The first is the social license approach, where the burden of identifying and treating heritage is placed on the project proponent, and the second is the national patrimony approach, where responsibility for heritage is vested in the government. These approaches are not mutually exclusive and most countries adopt elements of both, although one usually predominates.

Many countries place the responsibility of complying with cultural heritage laws and regulations on the project proponent. Underlying this approach is the proposition that the party responsible for causing potential damage to a community's cultural heritage should bear the costs of determining what part, if any, of that cultural heritage is threatened or at risk and then should pay for whatever mitigation the community and its authorities deem appropriate. Social license implies that a community's acceptance of a project is conditioned on the proponent's agreeing to specific requirements, some of which may refer to protecting and conserving cultural heritage. Underlying the license is the requirement to comply with all laws, regulations, conventions, charters, and safeguards placed on the project proponent by government agencies and funding institutions. Beyond these tangible requirements, the proponent needs to engage and gain the trust of heritage experts and stakeholders (see EXPERTS AND STAKEHOLDERS) for the life of a project, which, in the case of infrastructure or resource extraction projects, can last for years, or even for decades.

The social license approach has one major flaw, in that it is paid for by the project proponent. And, given that the motivations of project proponents are to complete their project, cultural heritage is almost always viewed as something to be done as quickly and cost-effectively as possible. Without a strong, consistently and effectively enforced system of regulations, it is generally left to the proponent to decide how much effort, if any, should be placed on identifying, evaluating, and treating heritage resources. Efforts in these areas are often minimal, because it runs counter to the developer's motivation to find things that

will impact the progress or outcome of his/her project. Unfortunately, on this approach, local and descendant communities are often left out or marginalized and have little opportunity to comment on the results of studies funded by the proponent, which often claim that few resources exist to be impacted. No one should be surprised that, when heritage resources are found during the project, conflicts arise.

Some countries view their heritage as national patrimony (see HERITAGE AND NATIONALISM), and thus centralize responsibility for all aspects of CHM with the government. These countries argue that their cultural heritage is too important to be treated as a commodity. Altschul (2018) explains that, in the national patrimony system, the government determines the proper balance between heritage conservation and economic development; defines the financial and human resources needed to maintain this balance; allocates the resources; performs the necessary CHM services; and determines whether the services were performed appropriately. A national patrimony system makes CHM a government monopoly. There is little incentive for government workers to meet a budget or schedule, and lack of accountability, corruption, political pressures on CHM professionals, and inadequate treatment of heritage resources are often common occurrences. On this approach, CHM becomes a top-down activity, which often leads to the creation of a national narrative at the expense of local and descendant community heritage (as in the social license approach, the opinions of these communities are not taken into consideration).

Regardless of whether a country's CHM system adopts a social license or a national patrimony approach, the success of its CHM framework depends on meeting four requirements (Altschul 2018). First, CHM has to be resourced both financially and with adequate numbers of sufficiently trained CHM practitioners. Second, local and descendant communities must be empowered to be part of the system and be integrated into it. Third, there are strong government regulations and oversight of CHM; and, fourth, there is independent verification of the processes and services by objective experts. In some developing and transitional countries, successfully meeting the four criteria requires establishing a new CHM

system. Major infrastructure projects may offer the perfect opportunity to develop a country's comprehensive cultural heritage program (see Gunchinsuren, Altschul, and Olsen 2011 for Mongolia and Stokin, Novšak, and Plestenjak 2008 for Slovenia).

Regulatory frameworks and heritage safeguards

Currently, one of the strongest systems of heritage law is in force in the United States, and the highest level of protection is afforded heritage resources found to be significant (or potentially significant) according to the criteria for listing in the country's list of heritage places (the National Register of Historic Places, established by the National Historic Preservation Act [NHPA] of 1966). Heritage protection is generally only reserved for resources impacted by federal undertakings, although some of the states and municipalities have laws that follow to a greater or lesser extent the federal law. These laws also have procedures for assessing and mitigating the impacts of projects on resources and for stakeholder involvement. There is some overlap between environmental and cultural resource legislation. At the federal level, heritage protection is centralized for resources on lands owned and managed by the government and on projects for which federal permits are required. Although the system established by the NHPA has generally worked well, a major flaw is that the focus is on resources with identifiable boundaries (e.g., archaeological sites, buildings, and structures), and not on less tangible aspects of heritage. Influenced by international approaches to managing heritage resources, other designation programs have developed that incorporate a more holistic notion of heritage values. These include a focus on landscapes, traditional cultural properties, scenic and historic byways, geographic regions, and National Heritage Areas (Morgan et al. 2010). Public acceptance of these designation programs is variable and quite susceptible to changing political climate.

Other industrialized nations, such as various countries in Europe and the United Kingdom and its Commonwealth Countries and former colonies, have provisions for heritage protections

(see Carman 2015, 28–50 for the development of current structures), but these are quite variable and range from centralized to decentralized administration.

In developing economies CHM is much less consistently regulated, although many countries, including those in the “developing” category, have become states parties to conventions that protect, promote, and conserve cultural heritage—conventions adopted under the auspices of the United Nations Educational, Scientific and Cultural Organization (UNESCO) (see Altschul 2018 for an expanded discussion of these conventions). In fact many of the oldest and most widely known archaeological sites, some of which have been designated world heritage sites (see WORLD HERITAGE SITES DESIGNATION), are located in underdeveloped or developing countries. The World Bank classifies 140 countries in the world as “developing economies” (<http://data.worldbank.org/about/country-and-lending-groups>, accessed November 26, 2017). For the fiscal year 2018, 31 countries were defined by the World Bank as having low-income economies, which in 2016 meant a gross national income (GNI) per capita of \$1,005 or less. Another 53 countries were declared lower-middle income economies (GNI per capita between \$1,006 and \$3,955), and the 56 countries eligible for World Bank funding were classified as upper-middle income economies (GNI per capita between \$3,956 and \$12,235). Most lower-income countries are in sub-Saharan Africa, the other two groups being dispersed throughout Africa, Asia, Latin America, and eastern Europe.

Altschul (2018) explains that all developing economies accept aid, grants, and loans from industrial countries and from multilateral financial institutions (MFI) that the industrial countries support. Underlying the concept of economic aid is the belief that, in exchange for allowing the growth and expansion of private enterprise and public infrastructure, the well-being of the people and society in that country will improve. Most of the inhabitants of the countries that receive aid are skeptical of this assumption and generally believe that the rich and powerful will reap the benefits of economic development, leaving the plight of the common person unchanged. Altschul characterizes this dilemma as a “Faustian bargain,” and

others concur that CHM as a top-down activity has the potential to re-create paternalistic, colonial structures, given that external assistance often delays or obviates the development of a sustainable heritage management system within the country that receives assistance (see Murimbika and Moyo 2008 for a case study from Zimbabwe).

On a more positive note, MFIs such as the World Bank and the International Finance Corporation, which fund projects in developing countries, have been building cultural heritage safeguards into their loan processes. Private financial institutions are following in their step by also committing to the Equator Principles (Altschul 2018). Some multinational companies have issued their own guides for integrating CHM into their projects (e.g., Rio Tinto 2011).

Best practices

Responsible CHM follows an adequately scoped and funded inventory of tangible (and intangible, as applicable) heritage resources, evaluation, and mitigation of impacts, which may include resource preservation or avoidance strategies (see *ASSESSMENT: HERITAGE IMPACT (HIA)*; also Carman 2015, 79–155) or, in the case of historic buildings and structures, repurposing and adaptive reuse. The value or significance (see *VALUE OR SIGNIFICANCE*) of each resource is evaluated, normally in relation to research questions that were outlined and integrated into project planning from the beginning. Successful projects will integrate community involvement (see *HERITAGE AND COMMUNITY ARCHAEOLOGY*), as well as appropriate planning for project reporting and for the management and curation of digital, archival, and excavated materials. Public outreach (see *PUBLIC ARCHAEOLOGY*) should be built into projects whenever possible. Standards of practice should ideally be similar enough to promote data sharing, digital preservation, and access, and the support of the conservation of archaeological resources. Ideally, they would reflect standards and practice in the modern developed world. As McManamon, Stout, and Barnes (2008, 19) note, the “liberal’s dilemma” in archaeology relates to “whether professional

activities should be conducted strictly according to western, scientific standards and guidelines or should be changed to incorporate culturally relevant modifications when practiced in traditional communities.”

Occasionally the qualifications for CHM professionals are outlined in legislation or regulations, but more often the standards for practice come from entities such as the Register of Professional Archaeologists and the Institute for Archaeology, and as part of the ethical principles of professional societies such as the Society for American Archaeology, the European Association of Archaeologists, and the American Cultural Resources Association, among others (see *ETHICS IN CONSERVATION*).

Challenges

One of the greatest challenges facing CHM today is how best to assist developing countries in finding an acceptable balance between preserving their heritage and economic growth. It is also an area of great potential for using cultural heritage to redress the social inequities of the past and to advance social well-being. What can be done to build sustainability in the CHM sector? A country’s heritage should be translated into local economic and social capital and should involve capacity building. Only when local communities retain the sense of ownership for their heritage can site protection and heritage management become sustainable (Murimbika and Moyo 2008).

An equally vexing challenge is how to address the global issue of the uneven nature of academic training for CHM professionals, even though some universities have specific degree or qualification programs dedicated to heritage training. Differences between academically based research and CHM are profound. Biehl (2013, 45) recommends that the graduate curriculum in archaeology (preferably in collaboration with sociocultural anthropology) be modernized and redesigned so as to meet the increasing demand of heritage managers trained within an international and interdisciplinary framework. Training should also be available to museum studies and museum management graduates, tourist industry

managers, law and policy makers, and other professionals whose work interfaces with CHM.

SEE ALSO: Archaeology and Tourism; Designing and Co-Creating Heritage; Digital Heritage; Heritage: Nonwestern Understandings; Heritage and Conflict Resolution; Heritage and Economics; Heritage and Human Rights; Heritage and Landscapes; Heritage and Policy; Heritage and Politics; Heritage and Society; Heritage and Value-Based Approach; Heritage Business and Marketing; Heritage Ethics; Heritage Interpretation; Heritage Planning and Design; Predictive Modeling; Preventive Conservation in Archaeological Sites

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Heritage Planning and Design

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Heritage planning and design is here understood as an amalgamation of, or the intersection between, urban heritage and urban planning and design. In the past few decades, drastic changes in urban economies have resulted in an urban planning and design increasingly directed toward the reinvention of place. In particular, this has affected places that have been exposed to severe structural change. In the various urban planning and design ideals that have emerged as a response to societal development, the past plays different—direct or indirect—roles for future urban development. In many cases the past—for example, in the form of historical sites—is considered a resource for development, for example in place branding and marketing strategies. In other cases the past is seen as an obstacle to urban development or as having no value for it. Heritage planning and design also means an approach where projects are developed in harmony with the community and with all its inhabitants. Heritage-based planning and (urban) design can be seen as an approach to community development that sets a foundation for building and nurturing a unique, authentic, and place-based community identity and contributes to a sustainable economic base. This urban planning and design principle demands respect for the cultural heritage of a place and a balance with tradition.

Urban planning and design is a composite concept, and thus not straightforward in its meaning. Urban design can be described as architecture on a larger scale and within a broader context, or as a bridge between architectural design and urban planning. Urban planning is primarily concerned

with the welfare of the citizens; with water and land-use management, including transportation, housing, commercial and public services, communication networks, ecology, and many other urban issues. Planning can be distinguished as a process-oriented activity and design as a product-oriented activity. Hence urban planning and design is here understood as a cross-border field between the urban context, the planning process, and the design product. In this particular case, the urban context comprises the urban heritage.

Heritage and emerging processes of dealing with the past

The traditional view of heritage is that it consists of material remains from the past with historical values as defined by heritage experts. In urban heritage management, the common method has been identification and protection of monuments and well-defined areas on the basis of an authorized heritage discourse (AHD) (Smith 2006). Hence management has relied on expert values within academic fields traditionally concerned with cultural heritage, for example art history, architecture, and archaeology.

As expert values, these are assumed to correspond to values in society at large. Consequently, they are decided upon independently of the values held by other interests, which in general are based on completely different perspectives concerning the urban environment, for example perspectives held by urban planners and designers, real estate owners and developers, and, presumably, various groups of citizens. It is quite clear that in urban planning and design practice, in which concrete values of different kinds have to be weighed against one another, this assumed correlation between expert values and the values held by other interests is not at all axiomatic. Conflicts between various interests over how the urban environment should be managed are a common experience in practice. For a long time during the twentieth century, the development of the

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conservation movement presupposed that there is a fixed quantity of heritage objects with intrinsic value to be discovered by heritage experts. However, in the past few decades this view has been challenged, and it has increasingly been acknowledged that heritage and its values are produced and defined, and hence are a construct in contemporary society.

The evolution of approaches to the past during the twentieth century has, according to Ashworth (2011), resulted in three different approaches, which from the 1980s coexist in what Ashworth calls an incomplete paradigm shift: the *preservation paradigm* (from the late nineteenth century onward), the *conservation paradigm* (from the 1960s), and the *heritage paradigm* (from the 1980s). In short, the preservation paradigm can be considered a traditional perspective on the past, where experts are concerned with the intrinsic values of specific objects for the purpose of safeguarding them from development or any other form of harm. From an urban planning and design perspective, the preserved objects appear as irrelevant or as obstacles to development.

With the conservation paradigm, the focus shifted to include ensembles of objects in addition to individual objects, to integrate contemporary use into the equation, and to involve policy makers beside experts. In a nutshell, contemporary use became an essential part of local development and of the revitalization of places. The heritage paradigm acknowledges, in contrast to the preservation paradigm, that value is created in contemporary society. Accordingly, the focus is directed toward the use of the past in the present; hence the users, rather than the experts and the policy makers, are at the center of attention. Furthermore, the heritage paradigm acknowledges that all places—and not only so-called historic cities—have a past with potential heritage values to be used in urban planning, design, and development.

Harrison (2013) has differentiated between *official heritage* (objects and areas authorized by public bodies and protected through legislation) and *unofficial heritage* (objects and areas recognized by individuals or communities but not publicly authorized and formally protected). Urban heritage is a complex system of the official and unofficial heritage, but also of more modest

objects and other built structures, which are spatially or socially linked to one another, as well as to the official and unofficial heritage. Accordingly, a certain monument, object or structure within the system is to a large degree characterized by the urban context—that is, by the spatial, social, cultural, and economic circumstances that distinguish every place and thus impact every object or structure in a positive or negative way. It is this interplay between different parts of the system that defines the urban landscape as heritage, rather than the specific monuments and areas that are identified according to the AHD.

The systems view on urban heritage, which is aligned to the heritage paradigm, defines it as a cultural infrastructure, comparable with other infrastructures as a frame for people's daily private and professional activities. By tradition, the concept of infrastructure is associated with technical systems, for example roads and railroads. However, these systems are not “infrastructure” just by themselves, but have the potential to function as infrastructures. In other words, the actual use (in a broad sense) is significant for defining a built (or other) structure as an infrastructure. Consequently, viewing urban heritage as an infrastructure underlines its potential role for urban social and economic development, that is, as a resource in people's everyday private and professional activities. Following this reasoning, in order to use urban heritage in urban development work, it is necessary to include a wider group of stakeholders in the valuation process. Hence the task is, in accordance with the heritage paradigm, to define the urban heritage as an infrastructure based on how people use and benefit from the urban environment rather than based on the preservation paradigm, in which historical values are ascribed to specific monuments and areas by heritage experts.

The urban environment results not only from deliberate urban planning and design measures, but is also a complex product of those measures and of emergent societal processes and general development. Hence, to a large degree, the urban product also derives from economic, social, cultural, and spatial processes of structural change, including economic and cultural globalization, deindustrialization, a diminishing public sector, increased mobility, and tough territorial competition. Consequently societal processes and

developments challenge contemporary heritage management and, in particular, traditional ways of working with heritage issues according to the preservation paradigm.

Moreover, to address large-scale structural change, a number of theories and ideals have directly or indirectly influenced the practice of urban planning and design. On one side, past urban planning and design ideals and practice are revisited and advocated as a solution to many contemporary social, economic, and environmental problems, where modern planning and design is believed to have failed. On the other side, any relation to the past is considered obsolete, and thus irrelevant to contemporary urban planning and design and to future urban development.

Urbanisms: contemporary ideals of urban planning and design and the past

The specific theories and ideals—urbanisms—that influences today's urban planning and design discourse have been examined in various ways by different scholars, often resulting in differing categorizations and definitions (Olsson and Haas 2013). In particular, a few ideals stand out as exceptionally relevant here: reurbanism, new urbanism, and posturbanism—as well as everyday urbanism. These various urbanisms are based on different notions about contemporary society and on future prospects and therefore represent different ideas about the role of the past in urban development.

Reurbanism could be described as being oriented toward constant urbanity; in particular, it addresses the repair of the urban fabric. In that sense, this particular ideal is oriented toward adaptation to the existing urban environments, restoration, and interpretation of the historical and contemporary form of the city. Typical reurbanism projects are carried out in urban areas that have lost their function, such as former industrial sites and harbor areas. In particular, the traditional European city, with its grid street plan, is modeled to complement the existing city. An example of an ongoing reurbanism project is Hagastaden (Haga City) in Stockholm, Sweden,

which is a redevelopment project around a former marshaling yard adjacent to the inner city. Often reurbanism projects are geared toward the idea that the city is a constant urban fabric with an existing building stock and a new one that produces density and stable forms throughout the space of the urban grid (this was evident throughout the World Trade Center Site New York Design Competition).

New urbanism is rooted in the late nineteenth-century and early twentieth-century social reformist town-planning initiatives. Likewise, it has a social agenda and is based on ideas of mixed use, a neighborhood concept, and an emphasis on public space. It is thus focused on the (re-)creation of the past as a dynamic reference for present and future urban planning and design. In particular, it can be noted that physical structures and complete town-making principles have more importance than single objects. New urbanism projects are in general directed at establishing new settlements in the form of small towns; typical examples are Seaside, Florida in the United States and Poundbury in England.

Posturbanism could be described as generic hybridity with a focus on reinvention and restructuring. Hence the past is irrelevant, except (maybe) for certain monuments that have primacy as works of art. Nevertheless, objects are more important than the urban structure. The built environment functions above all as a contextual backdrop; in short, emphasis is put on architectural monuments and iconic flagship buildings—"starchitecture"—that claim to be innovative and to express a new era. Examples of posturbanism projects are the Guggenheim Museum in Bilbao, Spain by Frank Gehry and Burj Khalifa in Dubai, United Arab Emirates by Adrian Smith at SOM—the tallest structure in the world in 2017 (approximately 830 m/2,722 ft.).

In everyday urbanism the city is not decoded solely in terms of physical form but rather in terms of lived experiences, in other words narratives and daily life are the means of transforming urban form. Everyday urbanism infuses a cultural preservation and place-making approach into the planning and urban design process by emphasizing the built environment, the

citizen input, local character and history, narratives, memories, and a sense and image of the place—its tangible and intangible elements and assets. It also opens the doors to economic incubation.

Thus, ideas about contemporary and future society and approaches to the past are expressed in different ways in different urban planning and design ideals. New urbanism, just like reurbanism, is based on ideals and qualities from the time before modernist planning and is trying to re-create them in contemporary urban planning and design. Thus both reurbanism and new urbanism acknowledge the past as an important model for future development, but not necessarily in a way that is rooted in the specific history of a place. Posturbanism, on the other hand, connects to an idea that the past has no real relevance for future development. In that sense, it could be said to align with the preservation paradigm, in that heritage objects are considered to be obstacles to development. Everyday urbanism on the other hand sees place-based community redevelopment as action, through ideas and solutions based on urban fabric, social kineticism, historic buildings, and infrastructure as well as on the history, customs, and culture of each unique place.

While globalization tends toward a certain commodification and homogeneity of heritage and culture, successful global cities still have a strong individual and particular cultural identity. The economic value of the culture of cities therefore lies not only in the arts taking place there but also in each city's urban and social fabric, its architecture, and its cultural heritage (Monclus and Guardia 2006).

Designing the past: cross-disciplinary understandings of heritage

Regardless of which ideal of urbanism dominates in urban planning and design practice and which paradigm guides most of the approach to the past, the resulting urban heritage affects people's urban experience. It also either stimulates or limits their everyday lives and provides opportunities or restrictions for business development. In the end, urban heritage is all about "designing the past."

In any given situation and context, the dominant ideal in urban planning and design, together with the prevailing approach to the past, will define the specific urban heritage and thus will influence how we understand the past.

Historic preservation theories and tools need to reflect the notion that heritage and culture (and urbanism) are ongoing processes, at once evolutionary and inventive, not static sets of practices and things. Heritage planning and design builds on an understanding that history and culture are valued resources through which we view the world and understand the place of our past, present, and future. We therefore need to understand the critical methodological tools that are necessary to a professional engaged in the investigation, interpretation, and evaluation of the urban built environment. Heritage planning and design demands cross-disciplinary studies and an understanding of heritage conservation and urban planning with a broad practical knowledge of the laws, regulations, and policies that apply to planning and conservation practice knowledge of urban design, public policy, and architectural and planning history and theory.

Moreover, two important aspects—branches of heritage planning and design—need to be recognized: *cultural urbanism* and *heritage urbanism*. Cultural urbanism refers to the distinctive social and cultural patterns that develop in cities, reflecting local culture and authenticity that encourages social interface (Meyer 2014). Heritage urbanism is essentially based on the principle that the heritage should not remain only a monument to the past (a protected work of art), but be also an active participant (a creative subject) in the contemporary life of cities.

The traditional ways of working in heritage management—mostly the preservation approach, but also conservation approaches that emphasize historical monuments and well-defined conservation areas from the perspective of heritage experts—imply that modest objects and the general urban landscape will be neglected and that a systems view on urban heritage will therefore not be acknowledged (curatorial preservation: closed and locked urban heritage). Urban heritage—with its physical and social qualities—is situated in a spatial continuum in which the interplay between different features and their relational meanings becomes an important value category in

contemporary urban planning and design aiming at urban development (urbanistic preservation: open systems urban heritage).

SEE ALSO: Authorized Heritage Discourse; Community Heritage; Faro Convention; Heritage Management; Planning and Tourism

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FURTHER READINGS

Heritage: Nonwestern Understandings

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During the nineteenth and early twentieth centuries, the concept of heritage was largely associated with historicity, westernized aesthetic considerations, and the preservation of material heritage such as objects, buildings, monuments, and sites. From the middle of the twentieth century, nostalgia for the past led to the development of the heritage industry and the growth of public museums and heritage sites. From the 1970s onwards, civil rights activism and international efforts to establish universal principles for protecting cultural heritage turned the focus of dialogue about heritage upon the diversity of cultural and social practices and values and the various forms and functions of heritage in different cultural contexts. By the mid-1990s, however, it had become widely accepted that definitions of “cultural heritage” needed to be revised in order to reflect the diverse values and aspirations of different peoples. Heritage is now recognized as diverse and dynamic; and, while traditions and customs are a vital part of it, heritage is constantly being redefined and reshaped, and given new meanings and purposes.

In recent years, professionals in heritage-related disciplines such as archaeology, anthropology, historical interpretation, museum curation, and conservation have become more responsive to the concerns of other communities, whether indigenous, local, or source communities. Recognizing the rights of source communities as traditional custodians and decision makers, they have been engaging in dialogue, collaborative research, and community projects. These professions are also becoming more culturally diverse as more indigenous peoples and members of minority ethnic communities undertake university training and enter professional pathways into disciplines such as archaeology,

museum curation, and heritage management. As a result, the concept of heritage has been evolving and there has been a diversification of professional practices that better reflects the cultural values attached to heritage in its various forms.

World heritage

In the 1960s and 1970s, there was growing recognition of the fragility of the natural and cultural heritage and of the need for international action to initiate heritage protection strategies at national and international levels. Through its various agencies and programs, the United Nations was one of the key mechanisms for international discussions, providing opportunities for the participation of peoples from across the world. At the same time, civil rights campaigners, newly independent, formerly colonized nations, and indigenous peoples across the world were expressing their grievances on various issues such as self-determination, cultural heritage, lands rights, biodiversity, and intellectual property rights.

In 1970 UNESCO adopted the Convention on the Means of Prohibiting and Preventing the Illicit Import, Export and Transfer of Ownership of Cultural Property, which was designed to provide a mechanism for helping nations recover illicitly trafficked art and antiquities; and the UNESCO Convention Concerning the Protection of the World Cultural and Natural Heritage (the World Heritage Convention) was adopted in 1972.

Many local communities and indigenous people played a central role in discussions about cultural diversity and heritage, articulating their concerns and demands within the framework of human rights. Many value tradition and cultural heritage not just in terms of nostalgia or as an industry that can be exploited for economic development, but as an intrinsic component of efforts to sustain their own cultural practices and to maintain cultural distinctiveness in the face of globalization.

Indigenous writers and activists emphasized the religious and spiritual dimensions of culture

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and highlighted the contemporary significance of “heritage” materials as part of living cultures. Intangible and spiritual aspects of culture were identified as part of the complex of characteristics that comprise culture. The efforts of indigenous peoples to regain rights to traditional lands and to halt further losses and the destruction of sacred sites were significant in illuminating the subjective nature of human responses to landscape and the continuing links between humans and the cultural and spiritual associations with the natural world. Initially the criteria for listing reflected the dominance of western perspectives on cultural heritage as historical and material manifestations in the forms of buildings, monuments, and sites.

With the increasing diversifications of values expressed in discussions, heritage was recognized as subjective—a cultural construct reflecting the diverse and localized meanings and values attached to places and objects. New criteria for the World Heritage List were adopted in 1992 to include cultural landscapes, a term that better reflects the true extent to which cultural heritage and natural landscapes are intertwined. The first cultural landscape to be inscribed was Tongariro National Park in New Zealand, in recognition of the cultural and religious significance of the mountains for the Maori people; it had previously been inscribed in recognition of their outstanding natural values. In 1994 the Uluru Kata-Tjuta National Park in Central Australia was inscribed as a living and associative cultural landscape of the traditional owners, the Anangu Aboriginal community. The World Heritage List now includes a greater diversity of cultural sites, with over 102 properties described as cultural landscapes.

Intangible and living cultural heritage

From the early 1990s onward, there was also growing awareness of the importance and fragility of intangible forms of cultural heritage such as language, literature, folklore, music, dance, theater, rituals, and ceremonies, which promote creativity and express identity. This movement further highlighted the biases of the prevailing ideas of heritage and became a central focus in discussions concerning the need for nations to

develop strategies and programs to protect and promote cultural diversity.

The first legal instrument to specifically address the protection of intangible cultural heritage was the Recommendation on the Safeguarding of Traditional Culture and Folklore (RSTCF), adopted by the UNESCO General Conference in November 1989. In 1998, the Executive Board of UNESCO launched the Programme of the Proclamation of Masterpieces of the Oral and Intangible Heritage of Humanity, emphasizing the importance of living, intangible heritage as part of world heritage. This parallels the 1972 Convention on World Cultural and Natural Heritage and its adaptation to include cultural landscapes.

The importance of cultural diversity and of intangible aspects of heritage has been reinforced in a number of other international statements, agreements, and programs. These include the Nara Declaration on Authenticity (1994), the revisions to the Burra Charter in 1999, the Tokyo Declaration on Cultural Diversity and Heritage (2000), the UNESCO Universal Declaration on Cultural Diversity (2001), the UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage (2003), the UNESCO Convention on the Protection and Promotion of the Diversity of Cultural Expressions (2005), the Faro Convention on the Value of Cultural Heritage for Society (2005), the UN Declaration on the Rights of Indigenous Peoples (2007), and the Promotion and Protection of the Rights of Indigenous Peoples with Respect to Their Cultural Heritage, a study by the Expert Mechanism on the Rights of Indigenous Peoples (2015).

In the UNESCO Convention for the Safeguarding of the Intangible Cultural Heritage it is noted that intangible cultural heritage is sometimes referred to as “living cultural heritage” and that it is “transmitted from generation to generation, and is constantly recreated by communities and groups, in response to their environment, their interaction with nature, and their historical conditions of existence. It provides people with a sense of identity and continuity, and its safeguarding promotes, sustains, and develops cultural diversity and human creativity” (UNESCO 2003).

The concept of living cultural heritage emphasizes the creative and dynamic nature of culture

and heritage as continually adaptive and changing and highlights ongoing practices as primary mechanisms for preservation and cultural renewal. In many indigenous and traditional communities, elders are respected for the knowledge and skills they possess and are recognized as essential to the performance, transmission, and continuity of traditional knowledge and customs. The continuing practice of intangible cultural heritage can be a key mechanism for facilitating cultural renewal and for healing the effects of postcolonial trauma; in these circumstances cultural heritage is a necessary part of cultural survival in the present and in the future.

In Japan and Korea, key individuals whose practices and teachings were essential to preserving intangible forms of heritage were designated “living cultural treasures.” In 1993, the Republic of Korea proposed to the UNESCO Executive Board the establishment of a UNESCO Living Human Treasures program, which led to its launch in 1994. Member states are encouraged to implement systems for the official recognition of living human treasures whose knowledge and skills enable the performance and transmission of intangible heritage, and to develop strategies that encourage these individuals to further develop their knowledge and skills and transmit them to younger generations.

Heritage and human rights

As newly independent nations, indigenous peoples, and local communities became more active in discussions about cultural diversity, heritage, and human rights, they voiced their criticism of dominant western scientific research practices in fields such as archaeology and anthropology and called for western heritage professionals and institutions to recognize their rights to control, manage, and interpret their own heritage.

During the United Nations International Year for the World's Indigenous Peoples (1993) and the UN Decade of the World's Indigenous Peoples (1995–2004), a number of conferences were held in different parts of the world to address indigenous peoples' concerns about the environment, cultural and intellectual property rights, the exploitation of natural resources,

indigenous knowledge, and cultural heritage. An international conference organized by the Commission on Human Rights' Working Group on Indigenous Populations dealt specifically with the cultural and intellectual property rights of indigenous peoples. An outcome of the conference was the Mataatua Declaration, which called on states and national and international agencies to recognize indigenous peoples as the guardians of their customary knowledge with the rights to protect and control its dissemination. It also asserted the right of indigenous peoples to create new knowledge based on cultural traditions, emphasizing the dynamic nature of cultural heritage and its continuing link to peoples' present and future lives.

These sentiments were further emphasized by Indigenous Australian lawyer Terri Janke (1999) in *Our Culture, Our Future*, in which she identified 17 rights for which indigenous people were seeking recognition, reflecting concerns for protection and management of their cultural, religious and spiritual knowledge and materials. These include rights to define, manage, preserve, protect, and control indigenous cultural objects and indigenous ancestral remains, as well as natural resources and intangible forms of heritage.

The increasing importance that was placed on intangible heritage demanded changes to practices in disciplines and institutions that had previously operated within the western paradigm and that equated heritage with materiality and the past. This has seen a rise in community archaeology and history projects and greater collaboration between museums, local communities, and source communities—the cultural, ethnic, and religious communities from which artifacts originate.

Institutions such as museums—which have traditionally dealt with tangible heritage—have been challenged by the increased emphasis upon intangible heritage and by the emphasis that indigenous people have placed on the importance of intangible and spiritual aspects of heritage and in the continuing relevance of heritage to the lives of many communities. Their concerns highlighted the inadequacy of western notions of heritage and the differing values and multiple meanings that objects in museum collections

have for source communities, for the scientific community, for museums, and for governments.

In response, legislative changes and professional guidelines have been introduced in a number of countries to encourage museums to recognize the cultural heritage rights of communities, to work collaboratively with indigenous peoples, and to develop repatriation policies and practices. These documents encompass references to spiritual dimensions of heritage and reflect the diversification of the concept of heritage.

As museums and communities work more collaboratively, curators and conservators have learned more about the cultural and religious significance of the heritage materials for which they are responsible and have gained greater insights into the importance that some of the items in collecting institutions can play in maintaining and renewing cultural practices in the source communities.

Museum curators and conservators increasingly consult with religious practitioners in indigenous communities and major world faiths, to learn about cultural protocols and methods of care that should be used when working with sacred, ceremonial, or ritual objects. In some societies, sacred and ceremonial objects should be handled and conserved according to strict protocols, such as removal from display, specific methods of handling and storage, use or avoidance of certain conservation materials, or restricted, gender-specific access. Certain types of sacred objects are regarded as living beings that require particular forms of care such as feeding, the breathability of materials used for storing, or the practice of rituals that protect those handling them from powerful and potentially harmful forces. Some museums have been adopting culturally appropriate methods for storing, displaying, and conserving objects.

The 2005 Faro Declaration was explicit in stating that “knowledge and use of heritage form part of the citizen’s right to participate in cultural life as defined in the Universal Declaration of Human Rights” (Council of Europe 2005). This reinforces some claims for the repatriation of culturally significant materials, in particular funerary, religious, sacred, and ceremonial objects. However, the concept of world heritage value has been used by some directors of universal museums to argue

for the retention of important cultural materials and to resist repatriation claims.

Dissonant heritage

Heritage is acknowledged today as being diverse in nature and purpose, with multiple producers and forms. The democratization of heritage both reflects and facilitates the participation of different groups or “heritage communities,” which are defined in the Faro Declaration as those groups that “value specific aspects of cultural heritage and act to sustain and transmit it to future” (Council of Europe 2005, Article 4; Kisić 2013). Multivocality in heritage discourse facilitates the (re)interpretation of history by heritage communities, giving voice to those who were previously marginalized—minority ethnic groups, indigenous people, women, the LGBT community. The result is the creation of “dissonant heritage”: the presentation of historical narratives and multiple viewpoints that challenge conventional or dominant versions of history and deconstruct notions of a unified national or universal heritage.

In *Dissonant Heritage: The Management of the Past as a Resource in Conflict*, Tunbridge and Ashworth (1996, 20) contend that heritage is “a contemporary product shaped from history.” History itself comprises “selective attempts” to describe what has happened in the past, processes that legitimize some viewpoints while excluding others; therefore all heritage is, to a greater or lesser degree, dissonant. Tunbridge and Ashworth identify four of the most common contexts in which dissonance is active in the heritage sector (1996, 21–29). The first is a context where different sources present several conflicting culturally bound messages in the interpretation of “the same or related heritage.” As an example, one might consider scientific, Christian, and indigenous versions of human origins and the First People. The second context is one where alternative meanings are constructed by those receiving a message—meanings that are shaped by the recipients’ existing knowledge, beliefs, and values but are different and sometimes conflicting with the messages intended by the interpreter. Third, dissonance can be created when changing values occur within society or

within a cultural group, but the interpretation of heritage does not reflect those changes. This can result in presentations of heritage interpretation that reinforce dominant historical narratives rather than reflecting revisionist views of history; examples include the continuing interpretation of European colonial history in the Americas and Australia using terms such as “discovery,” “settlement,” and “battles” rather than acknowledging those events as “invasion,” “massacres,” and “genocide.” The fourth context is the interpretation of “difficult heritage”: aspects of history that are uncomfortable or painful, such as sites of trauma, atrocity, or war. The interpretation of sites such as the Nazi concentration camps in central and eastern Europe, the “Killing Fields” in Cambodia, and the slave-trade sites in West Africa are examples of difficult heritage, also referred to as dark tourism or thanatourism.

Heritage interpretation by previously marginalized groups or colonized peoples enables them to assert their identity and to resist dominant discourses. The presentation of multiple perspectives in heritage interpretation provides opportunities for dissonance and moves heritage from the cultural realm to the political. The promotion of diverse values and interpretations of historical events can result in conflict and hatred, but dissonance in heritage can also facilitate reconciliation and intercultural dialogue and contribute to cultural renewal. In *American Indian Ethnic Renewal*, political and cultural sociologist Joane Nagel notes that inquiry can then shift from “the search for ... historical vestiges of culture” to “study of the means by which native cultures have endured and adapted and continue to develop.” As Nagel notes, “the view of culture as action, rather than artifact, is an empowering depiction, one that transforms the image of American Indians from helpless casualties of the overwhelming forces of history to powerful players in their own survival and renewal” (Nagel 1997, 72). In this way heritage becomes a mechanism by which the hegemony of the colonizers can be challenged.

SEE ALSO: Authorized Heritage Discourse; Countermapping; Heritage and Human Rights; Heritage Ethics; Plurality and Multivocality; Repatriation; World Heritage Sites Designation

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Memory

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Heritage and memory

Heritage as a form of memory directly linking the past (heritage and history) with present-day considerations, values, and expectations and is today widely recognized in many types of research, institutions, and communities. Society once used (controlled) history, archives, museums, and different forms of active remembrance (narratives, symbols, commemorations, monuments, memorials, and protected memory sites) to represent its past and identity. Today, memory work is part of not only public policies but also innumerable everyday citizen practices, creating complex interwoven relationships within family, neighborhood, community, interest groups, and organizations.

The recent growth of memory studies in research relates to shifts in many disciplines. The recounting of historical facts has been replaced by an understanding of the politics of remembrance and the interpretation of history within collective memory. Archive research has been complemented by extensive oral history focusing on personal memories and the emotions of common people. Political sciences have been put at the heart of nation-building by means of social (state, public) memorization and memorialization. Cultural studies have refocused their attention towards how the past is re-presented in popular narratives. Sociology and psychology, facing policy demands to understand social conflicts, trauma, and needs of reconciliation, have also developed approaches to memory production and transmission. Philosophy contributes reflections on memory, forgiveness, and reconciliation. Cultural resource management uses memorized intangible heritage as a key resource for development.

Cultural and other public policies have drawn attention to the politics of remembrance and oblivion because of the many dissonant issues raised within the politics of reconciliation after World War II, post- and neo-colonialism, and especially within UNESCO efforts to support cultural diversity and intercultural dialogue. Issues of memory and oblivion have been central to those debates due to controversies and discrepancies in interpretation of the past, especially linked to heritage with different meanings for different communities (so-called dividing or dissonant heritage).

UNESCO's Lists of World Heritage and World Heritage in Danger are important instruments for memory issues, especially the latter, "which focuses on heritage that is disappearing due to wars and armed conflicts, natural disasters, the consequences of industrialization or pure neglect" (especially when it comes to the "heritage of others," such as the heritage of communities that no longer live in a certain territory). Putting heritage on the list inscribes them in a collective memory of the world, raising interest in their preservation, understanding, and interpretation.

Cultural policies have been making a special contribution to the deepening of the heritage and memory issue by efforts to negotiate around dissonant heritage, asking museums, archives, and other heritage institutions to reconsider their permanent collections and open them to individual and collective memories that until recently have not had a place in them.

History of memory research

An implicit concept of group memory has existed since Greek times, but the history of memory research and memory studies begins in 1925 with Maurice Halbwachs' book *Les Cadres Sociaux de la Memoire* that introduced a concept of collective memory. In the 1980s Pierre Nora further developed memory studies by introducing the notion of *lieux de memoires*—material or immaterial symbolic elements of the memorial

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heritage of any community. Reprinted in English in 1998, this work had enormous impact on many disciplines (historiography, archaeology, anthropology, and cultural studies) (Nora 1998).

In the 1990s several “memory schools” developed in Europe and North America. In Germany, Jan and Aleida Assmann reflected on the importance of cultural memory for nation building and the rise of nationalism, developing a body of work that developed important ideas such as distinctions between cultural, communicative, functional, stock, and intergenerational memories. Through numerous projects such as “The Past in the Present: Dimensions and Dynamics of Cultural Memory,” they have contributed to the development of memory studies and to a new culture of memory.

In the UK, Tony Bennett and other academics have revisited the notion and concept of museums as keepers of national past, using the term “memory machines” (Bennett 2004), while Paul Conner (1989) developed the concept of embodied memory by discussing how societies remember or forget, analyzing in its ceremonies socially negotiated practices expressed in manners, clothes, bodily gestures, and creation/use of place.

In the United States, scholars such as Andreas Huyssen are discussing “present pasts” and “amnesia”—how the past today is remembered or forgotten in media and politics, focusing especially on interpretation of visual expressions (Huyssen 2000). Marianne Hirsch meanwhile has introduced an important concept of “post-memory” (Hirsch 1997).

In Latin America and southeast Europe, interest in the culture of memory was linked to social traumas and memory transmission related to troubled pasts. Individuals and families connected by similar political persecution or war trauma (mass killings, “mass disappearances”) have nurtured transgenerational memory transmission as well as specific mutual contacts in order to fight government-supported social amnesia. That, together with explicit misuse of history and the manipulation of memory by governments (such as the project of antiquization in Macedonia called “Skopje 2014”), provoked scholars to approach issues related to the politics of memory and oblivion so as to demonstrate how far those policies inhibit social development, reconciliation, dialogue, and integration.

Paul Ricoeur (2009), for example, has questioned why certain historical events are memorialized as part of public policies everywhere (within the process of EU integrations all new democracies in Europe have built Holocaust museums), while other events of similar significance and extent are put into oblivion and not shared as contemporary cultural memory (e.g., the French war in Algeria). An important part of his work is devoted to oblivion and forgiveness, ethical considerations related to the truth of historical knowledge, commanded forgetting (amnesty), forgetting and manipulated memory, and forgiveness and forgetting as such—scrutinizing political strategies that deal with memory and reconciliation.

Memory policies

In the nineteenth century, implicit politics of memory and oblivion included heritage but were related more to ideology and politics (national identity) than to safeguarding heritage and memory for the sake of preserving cultural identity. The politics of remembrance and oblivion had been creating “appropriate” links between past and present within public space, but only through selective narratives that contributed to the sacralization of certain historical moments deemed suitable for ceremonies, celebrations, and commemorations (Assmann, Assmann, and Konrad 2010). These national processes of constituting collective consciousness and collective memory were done through three methods: *historization*, *aesthetization*, and *nationalization*. In *historization*, narratives idealized selected historical events and personalities (usually linked to independence, the creation of state, the Constitution). Within *aesthetization*, national cultural and artistic canons were created that reached every citizen through public education, thus contributing to a common cultural memory. *Nationalization* chooses only narratives, events, and visual representations that are thought crucial to the creation of national identity and character and that should be embedded in every individual and every subgroup of the nation. Although those processes and methods might seem spontaneous, they were politically led.

Paul Connerton identified seven types of forgetting: repressive erasure, prescriptive forgetting, forgetting as a necessity for a new identity, structural amnesia, as annulment, as planned obsolescence, and as humiliated silence. Two more reasons might be added: forgetting as a confused silence, and forgetting as a shameful silence. Different societies practice different types of oblivion. For totalitarian and authoritarian regimes, repressive erasure is a main strategy; in democratic societies, prescriptive forgetting is used if authorities believe it beneficial for all parties (e.g., a controversial event). Structural amnesia, very close to shameful or confused silence, occurs when there is a social consensus that some event (such as collaboration during occupation) is shameful or degrading for the picture that nation wants to build around itself. In those cases, monuments or other heritage artifacts are often forgotten, even if not destroyed or removed. Numerous statutes, for example, have in recent decades been removed from the public realm in Europe for ideological reasons, official memory policies seeing them as a danger to current political and social values. Sometimes they are put in new “sculpture parks” (e.g., Budapest, Druskininkai, Lithuania, or Moscow) but many are destroyed or sent to museum depots.

National public memory policies became a focus for academic research quite recently because of the use of heritage and memory in identity creation. Links have been clearly identified in many studies, showing ways of identity construction and representation from the mythologizing of historical persons and events (from Jeanne d’Arc in France to Abraham Lincoln in the United States) to the invention and misrepresentation of historical facts due to present political ambitions (e.g., conflicting interpretations of Alexander the Great in present-day Greece and the former Yugoslav Republic of Macedonia).

Globalization and migrations, on one side, and the creation of supranational communities such as the European Union (EU), on the other, demanded a new approach in reconsidering world history and world heritage as a common memory of the humanity. Retelling the past became a new policy demand of multicultural societies needing to generate a revised sense of a collective identity. Scandinavia, for example,

must integrate a Sami past into its memory, while all EU countries must deal with the shared troubled past that divided them throughout history; the role of heritage in conflict resolution has started to attract more interest (see *HERITAGE AND CONFLICT RESOLUTION*).

In some regions, such as the Mediterranean and South America, those initiatives do not have clear support from public bodies and relate mostly to the endeavors of independent groups and cultural communities that would like to bring their common standpoint to the memory of the world. The UNESCO program “Memory of the World” aims to list the documentary heritage of different countries that until now have been part only of national pride, and to highlight common heritage in regions that have not been widely known. For example, “American colonial music,” a documentary heritage submitted by Bolivia, Colombia, Mexico, and Peru, offers sixteenth- to eighteenth-century music from different countries of the American continent (as a testimony to the acculturation processes between indigenous, African, and European cultures). A similar example is the “Archive Middelburgsche Commercie Compagnie” submitted by the Netherlands, Curacao, and Surinam to enable better understanding of the slave trade in the eighteenth century. Such multilateral entries are still in a minority, however.

Bottom-up public memory creation

Civil society and artists have begun to connect their projects to bottom-up memory community movements. Accessible technologies open multiple possibilities for artists to actively relate to community heritage and memory. Video testimonies and oral history enable “heritage” to be broadened to include dialects, customs, and the artifacts of everyday life or of specific “overlooked” professions. Exhibitions such as “Armenians in Grenoble,” the life of miners in the Ruhr in Zollverein, or about contraceptive pills in the Hygiene Museum in Dresden were based on intangible heritage and artifacts collected together purely at the moment of the exhibition’s preparation because there were no pre-existing museum collections or custodians. In the United

States, Fred Wilson's exhibition "Mining the Museum" (1994) addressed historical injustices never seen in official heritage and memory spaces such as museums.

The artist Jochen Gerz uses participative methods to engage communities in searching forgotten issues linked to the negative past (i.e., German Nazism) and to create "counter-monuments," such as the "Monument against Racism" in Saarbrücken (Vickery and Manus 2016), the commemoration of 2,146 destroyed Jewish cemeteries on the *underside* of newly laid paving stones in a public square outside the provincial parliament now named "*Square of the Invisible Monument*." Such artistic projects in the long run contribute to a questioning of historical reinterpretation and returns forgotten issues to collective and cultural memory.

Local communities and groups linked in different ways are creating their own memory sites, monuments, or collections (real or virtual), wanting to contribute their individual memories and objects to the public realm, thus widening perspectives on official heritage and memory definitions. Often, they erect monuments in public spaces to directly transmit the message of a community fighting for forgotten values and claiming their right to offer their own interpretation of history. They became much more active in fighting for the status of local tangible and intangible heritage, finding inspiration and support in the new instruments of cultural policies such as the UNESCO World List of Intangible Heritage and the Council of Europe's Faro Convention (2005), but there are many other examples.

SEE ALSO: Community Heritage; Cultural Resources Management; Designing and Co-Creating Heritage; Faro Convention; Heritage and Conflict Resolution; Heritage and Nationalism; Heritage Interpretation; Memory and Remembrance; World Heritage Sites Designation

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Planning and Tourism

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Introduction

By the early 1970s, considerable mistrust of tourism had built up, because of the negative impacts experienced by communities, thereby resulting in calls for more sustainable tourism. Sustainable tourism can be defined as tourism development that achieves an ongoing balance between economic benefits and social/environmental costs. The development of sustainable tourism has required effective and integrated planning processes to ensure that a host community and its cultural assets could absorb tourism and not allow it to dominate them. By integration in planning, people began to think of heritage, tourism, and conservation in one breath. With careful tourism planning, opportunities could be discovered and challenges could be faced.

Many different planning models have been devised over recent years to assist site managers in achieving sustainable tourism (e.g., Pedersen 2002; du Cros and McKercher 2015; Heritage Preservation 2016). They all share a number of features in common. In summary, the planning process involves the following ten steps:

- Background research and documentation
- A realistic assessment of the current situation, including an internal and external analysis
- Stakeholder consultation (undertaken at all stages)
- Specialist studies, as needed
- A realistic assessment of the site's potential to function as a tourism product and what measures are needed to achieve that potential
- Identification of options and the selection of the most feasible
- Establishment of a mission or vision

- Establishment of quantifiable and assessable goals and objectives
- Creation of specific action plans to achieve the goals and objectives
- Establishment of an evaluation and feedback mechanism to monitor achievement of the plans' objectives (du Cros and McKercher 2015).

Auditing tourism potential

The market appeal/robusticity matrix (du Cros 2001) is a proven assessment tool that can be applied in a proactive manner to assess tourism potential and identify management options prior to selecting a preferred site out of a number of options at a destination. It is predicated on the integration of different elements that constitute its two axes. The robusticity axis focuses on issues relating to cultural and physical values, while the market appeal axis reflects product and experiential values (see also du Cros and McKercher 2015). It can also be used to guide the planning process at the preferred site in order to identify fatal flaws and obvious impacts to be avoided.

The planning process

A planning process for sustainable tourism is usually best applied early in the transformation of an archaeological site into a tourist attraction. This is also the time when the process is most likely to be endorsed by all parties with a clear leader and a system agreed upon for them to work together. It is at this stage that some fundamental questions need to be resolved, such as:

- What kind of transformation of the site (sometimes also known as commodification) is appropriate to make its archaeological values more understandable to tourists, while being safe and pleasurable for them to visit?

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- Also, what is the best way for the site to tell its story to tourists?

At this early stage, social and physical carrying capacity is of key interest. In particular, consideration of the total visitor numbers, visitor flows, and the impacts of seasonal or daily peaks in visitor numbers must be considered to prevent negative impacts from potential overuse for tourism (UNWTO 2004). Also, what role does the site play in the surrounding host community and what involvement will they expect in future tourism operations.

When sites have a clear financial orientation, the ability to generate sufficient income and an acceptable return on investment must also be considered. This step may involve presenting and evaluating a number of use scenarios for consideration. Typically, scenarios represent low, medium, and high use, or low, moderate, and high commodification. Commodification encompasses all the typical changes that are made to make a site understandable and physically accessible to visitors, including tourists. Each scenario is assessed against the likely positive and negative impacts.

Once consensus has been reached about the desired approach, then more detailed strategic marketing decisions need to be made about whether and how the site can stand out in a crowded tourism marketplace. Sustainable tourism is best achieved when specialists in marketing and those in management work closely together or through an approach that integrates both from the beginning. To understand how marketing actions could enhance management requires a marketing situation analysis.

Marketing and planning

Conducting such a situation analysis is a vital though sometimes neglected step in the planning process. In order to succeed, a tourism development project must show a clear understanding of the site's strengths, weaknesses, and limitations, the structure of its target market, and their expectations. Failure to acquire this fundamental knowledge heightens problems such as the risk of inefficient allocation of resources; over-

or underestimating the size of the market; and failing to manage the visitor experience (Chhabra 2009; Colbert 2013).

The situation analysis should be able to answer the following three questions:

1. What products do I choose to offer/not to offer?
2. What markets do I choose to target/not to target?
3. What competitors do I choose to compete with/avoid?

The first two questions force stakeholders to consider the core product to be offered and the core products not to be offered and to whom. As a general rule, the deeper the experience represented by the core product, the smaller the market, while the shallower the experience, the potentially broader the appeal of the site. The decisions made here will influence the next questions—defining which markets to pursue and which competitors to compete against or avoid. These decisions, in turn, will be influenced by the position of the site in the attractions hierarchy at a tourist destination: primary, secondary, or tertiary. Primary attractions are the must-sees; secondary ones often draw tourists who have already seen all the primary attractions, say on a previous trip; and tertiary attractions are of less appeal than the other two (du Cros and McKercher 2015).

While adopting a marketing approach means considering archaeological sites as products, it also means acknowledging that some types of visitors are more desirable than others. Indeed, managing demand is one of the key goals of marketing (Colbert 2013). Many of the adverse impacts noted in cultural tourism are a direct result of the failure to adopt a marketing management perspective, rather than the opposite. As a result of failure to identify clearly the core product, the target market, financial and nonfinancial objectives and a plan of action to achieve them, mixed messages can be sent to visitors.

One of the problems with integrating a marketing approach is access to expertise. Most providers of cultural tourism products are either small businesses or operate on a not-for-profit basis. They have limited staff, often tasked with

multiple challenges including marketing, and even more limited budgets. A second problem is that few archaeological attractions have formalized marketing plans to evaluate their position in the marketplace.

Goal setting and action plans

Finding a clear mission or vision for the site as a tourist attraction is necessary, before the rest of the planning process can proceed. The mission or vision must be compatible with the cultural values of the site. This is as important as deciding the core product, market, and message. This phase will require input from the previous ones, such as a value-based or use assessment, an audit of its tourism potential, and situation analysis.

The vision needs to be transformed into a set of goals. They must be SMART: specific, measurable, attainable, realistic, and timely. Goals are the benchmarks by which the success or failure of a cultural tourism product will be measured. Interim or milestone goals should also be identified. This will help site managers assess how well they are performing and how likely they are to achieve their targets.

Action plans can be developed, once goals are established, to ensure they can be achieved. Such plans may include conservation, excavation, or monitoring of sites during development; actions for presenting and interpreting a site; marketing responsibly; avoiding or mitigating negative impacts and continued consultation and involvement of key stakeholders. Care must be taken to ensure that these plans are integrated and compatible.

Tourism experiences

Sustainable tourism experiences resulting from well-designed interpretation can inspire tourists to perform behaviors that enhance the environment on site and at similar places at home. All tourism experiences are subjective and firmly related to several factors including knowledge, awareness, recollection, and feedback. They are also closely tied to the activities at an attraction and during on-site visits. Themed touring

routes that give archaeological sites some context have been given much attention in recent years, because they spread economic benefits more widely and can assist the tourist in understanding more of the broader history of a region.

Telling the story

Some archaeological sites have a more complicated message than others to convey to tourists who may not know much about their cultural context. In some instances, these places may be visually and historically complex, as in the case of the Roman Baths in Bath, England. Potentially a confusing site, it has been clearly labeled and the remains and their histories are carefully pointed out.

The tourism planning process needs to consider employing a variety of old and new techniques for information presentation, where funding allows, to bring a site to life. They include the provision of signage (locational, advisory, and interpretative); incorporation of new communication technologies and existing audio-visual ones; interactive and participatory activities (including voluntourism); and the role of human site presenters.

Audio-visual techniques of a modest nature are still viable options to convey messages and experience an attraction, such as audio-tours and quick response (QR) codes for mobile phones. Accordingly, there are also tourists who are happy to buy books and DVDs to take home afterwards to continue to study and experience the site. Hence it is still worth considering first whether older or simpler techniques of conveying information could be worthwhile in a particular situation, before launching into more complicated plans.

A new area of digital technology that has great potential to bring many complex and/or fragmentary archaeological sites to life is that associated with “immersive” or “immersive virtual environments” (IVEs). Often these projects integrate high-resolution digital datasets from archaeological sites (photography and 3D models) with immersive and interactive display systems (Kenderdine 2013). For instance, the *PLACE-Hampi* project was created especially

for the Kaladham Museum near the Vijayanagar World Heritage Site, Hampi, India. It features animation as part of the 3D immersive imagery. The animation (Indian mythological characters) superimposed on the 3D imagery is similar in effect to augmented reality efforts at other sites.

Meanwhile, other new nondigital interactive activities are being devised to distract tourists from overusing popular sites and channel their energies elsewhere. One such project is a visit to the physical replica of Tutankhamun's tomb that has been made possible by using high-resolution recording and is a part of a key initiative by the Ministry of State for Antiquities to preserve the tombs in the Valley of the Kings. Accordingly, virtual tours, traveling exhibitions, and reconstructions are offered as an alternative to visiting the increasingly fragile Lascaux Cave Paintings in France. The most recently opened reconstruction is the Montignac–Lascaux International Parietal Art Center, or Lascaux 4, which employs different set designs, displays, state-of-the-art interactive workshops, and immersive technology to bring the paintings to life. Visitors have commented that the atmosphere inside the replica cave is just like that of a real cave: dark, damp, and muffled.

Archaeological “voluntourism” also has been growing in popularity as an on-site participatory activity for tourists. It is increasingly common for archaeological excavations to be fully or partly funded by nonspecialist participants. More recently some excavations can also be followed online, which gives prospective “voluntourists” an idea of what is involved in digging.

People are a very important aspect of information provision and in creating memorable tourism experiences. A professional guide can provide additional information to a tourist by contextualizing the site with visual aids. Often, simple methods work best, such as having some historic photos or plans to hand that can be used to show change over time, and are particularly useful for archaeological sites with long-running excavations.

Evaluation and feedback mechanisms

Evaluation and feedback mechanisms form the last step of a current planning process and the

first of a subsequent planning round. These mechanisms enable archaeological site managers to track success towards the goal achievement. As a minimum, experiential aspects of the attraction should be assessed through visitor satisfaction surveys, monitoring of social media, or other mechanisms. In addition, tourism impacts should be monitored by regular data collection for a longitudinal study (du Cros and McKercher 2015).

Finally, it should be noted that the work does not stop once an archaeological site is developed to its full potential for cultural tourism. Business models and budgetary planning should take into account the behind-the-scenes costs of maintenance, improvements to interpretation, archaeological site presentation, staff training, and other ongoing expenses as an ongoing process.

Future directions for planning and tourism

Along with further accommodation of technological change, attraction managers will have to contend with measures to adapt to climate change. Research in the United Kingdom has noted the need to establish a distinction between sudden, extreme events and long-term trends in order to develop strategies applicable to the wide variety of effects of climate change. It has been suggested that lack of long-term budgetary planning for managing and monitoring climate change impacts is becoming more of a critical issue for many heritage attractions (Hall et al. 2016). Stakeholder readiness to engage with these challenges varies immensely. Research is ongoing into the factors involved in barriers to stakeholder readiness to engage in these matters.

SEE ALSO: Archaeology and Tourism; Heritage Business and Marketing; Heritage Interpretation; World Heritage Sites Designation

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Plurality and Multivocality

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Archaeology has meaning not only for archaeologists. Pluralistic and multivocal approaches explicitly recognize the diversity of archaeology's stakeholders and question who should be allowed to speak for the past. They are political and theoretical positions rather than clearly defined methods, although they have generated new theoretical and methodological approaches too (Wylie 2015). Multivocality has moved beyond simply being a way of presenting or communicating and can be used to refer to an epistemological debate, a style of archaeological writing, a form of representation, field practice—or, ideally, all of the above.

The rise of multivocal approaches in archaeology can be situated within the rise of critical theory, postmodern, feminist, and postprocessualist critiques of archaeology. Theorists in this field have questioned the neutrality of the archaeological method by recounting the discipline's relationship with nation-state formation and its exclusion of certain voices (Fawcett, Habu, and Matsunaga 2008). Multivocality and pluralism are approaches that attempt not only to critique past and current practice, but to build a more hermeneutic experimental model. Meskell (2012) uses the term “hybrid fieldwork” to refer to an increasing blurring of disciplinary boundaries. Archaeologists now excavate archives, conduct ethnographic work on heritage, investigate media-based productions of knowledge, and work with living communities (Meskell 2012).

Multivocality is also a reaction to wider cultural shifts outside of the discipline, most notably the growing strength of “indigenous” and descendant voices in debates regarding cultural patrimony (Colley 2002; Sillar 2005). At its best, multivocal and pluralist archaeology represents a move toward a proactive rather than reactive approach to indigenous calls for consultation,

co-curation, and repatriation or reburial (Atalay 2008). However, archaeologists also need to be aware of the legacies of marginalization and exploitation, which they may inherit when trying to establish collaborative partnerships. Rhetoric regarding “other” voices in archaeology has traditionally focused on repatriation and reburial claims (Sillar 2005). However, multivocality, or “deep reflexivity” (Atalay 2008) involves radically rethinking the way in which archaeology is practiced, so that the entire process of interpretation is subject to analysis.

Multivocality and pluralism are less rulebooks and more umbrella terms that may be used to inform and describe wider debate and myriad types of research projects. Wylie (2015) differentiates between “syncretic pluralism,” where indigenous and scientific ways of knowing might be respected but are mutually exclusive, and “dynamic pluralism,” where indigenous ways of knowing may enrich scientific research. Appreciating the ability of oral traditions to preserve historical information is a case in point. In practice, multivocality and pluralism exist on a continuum or, more accurately, in a negotiated space where various types of fieldwork, ethnography, activism, and interpretation may overlap in different formations. It should also be an iterative process, as trust is built, power is shared, and practice is informed.

This type of approach has been popular with historical archaeologists in regions where engagement with living communities may inform the interpretive process in academically valued ways (Fawcett, Habu, and Matsunaga 2008). It has also become a necessity in places where the permission of descendant communities is a required element of access to archaeological resources (Colley 2002). However, the concept of a “first voice” or “originating community” can imply that, for an archaeological resource, there is a single true indigenous community that has a shared viewpoint.

A focus on the notion of legal genetic descent as the primary method of attributing rights can in fact be used to deny rights. “Indigeneity” is

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not an unproblematic concept, and official definitions can deny the complexity of postcolonial encounters and the agency of the communities in question (Sillar 2005). Definitions reliant on genetic descent have been used to disenfranchise groups that have long histories of migration or genetic “mixing,” or where time depth makes it impossible to identify direct descendants (Sillar 2005; Colley 2002). A focus on indigeneity can overlook issues of power, class, and local context within and beyond indigenous groups. There are also stakeholders who have shared histories of disenfranchisement but are not defined primarily by genetics or by their relationship with colonial encounter, for example working-class communities. Simplistic applications of multivocality summon up a false notion of one cohesive community, which lacks professional knowledge but brings indigenous “truth” in a way that is impractical, inaccurate, and offensive.

The notion of a shared community, or even of a family voice, simplifies the complex nature of cultural and historical affiliation and overlooks current research into the nature of identity (Atalay 2008). The idea of working with “a community” suggests a “them and us” in total consensus with each other. In multivocal accounts differences between voices may have to be compressed to create coherence out of a complex and ever-shifting picture. There may be imbalances of power related to education, gender, age, and family connections. For example, the mayor of a town may have a radically different viewpoint, access to power, and agenda from those of marginalized groups who live near a site, even though the latter could arguably be said to be from the same community. One person is unable to speak for a whole group. Stakeholders may be highly educated and politically astute and may have their own agenda (Atalay 2008). While multivocality and pluralism require the researcher to be an activist, s/he must work within local politics, for there is an arrogance in assuming that only outsiders can “give voice.”

Hodder (2005) argues that, when dealing with the existence of multiple stakeholders, there are two common reactions: policing the borders of the discipline against antiscientific interpretations; and adding other voices only in public interpretations. This second approach takes into account other voices but still keeps

them separate from the process of research. Examples of deeper collaborative and multivocal archaeological research exist on a continuum, and the degree of pluralism may depend in part on local context and politics. In some cases the entire research process can be shaped through collaboration: nonarchaeologists would set the research agenda from the start. The adoption of multivocal approaches happens mostly in historical archaeology, where different forms of evidence may intersect, and in “settler countries,” where the voices of different groups of descendants interact with those of ancestors and their material remains.

However, multivocality can also be seen in prehistoric archaeology, where a variety of stakeholders may express a spiritual or genetic link with communities long gone. Çatalhöyük is the site with the largest and longest running archaeological research project that is explicitly multivocal. In this instance multivocality recognizes that there might not be one community and that a site’s significance may cross religious, local, national, and international boundaries. Hodder (2005) also stresses that multivocality may take place in the very act of excavating. For example, decisions regarding where to excavate or how to take samples might be influenced by the specialisms, theoretical interests, and local practices of individual members of the team. Hence, if archaeologists were to hand over “pure data” to people outside the team in order to access other voices, that would still encompass certain assumed categories and processes (Hodder 2005). Such discussions prompted the development of a reflexive method at Çatalhöyük in which archaeologists questioned the nature of interpretation not only at the visitor center but in their sampling techniques, cataloguing, and finds analysis (Atalay 2008; Hodder 2005). This destabilized the divide between raw or pure data and subjective interpretations. At Çatalhöyük, site visits also allow lab technicians and fieldworkers to discuss priorities and to reflect upon the decision-making process that underlies their work and the different techniques used in different areas (Hodder 2005).

These interpretive discussions are recorded in videos and diaries, so that researchers are able to examine the context in which data are produced, both as they are conducting the research

and at a later date. These “rich descriptions” are interrelated via an integrated database. The Çatalhöyük database is available online, in an attempt to engage diverse groups in the process of interpreting the data. However, Hodder (2005) himself acknowledges that this technique of democratizing the interpretation is not without its flaws and that a great deal of archaeological data are incomprehensible to nonexperts.

Critiques of pluralism note the threat that engagement might make to scientific objectivity. Multivocal and pluralistic approaches have also been criticized for creating space for voices that might seek to oppress or misinform (see Wylie 2015 for discussion). The difficult question of who ultimately wields power or leads the process of collaboration in any given multivocal dialogue is something that is acutely realized by most of those who engage with these kinds of practices (Bender 1999).

Next, multivocality has been criticized for its lack of engagement with concepts of power. Identity is situational and intersectional; if research is to be truly multivocal, then conflicts and tensions need to be acknowledged and communicated. Attempts at multivocal interpretation can give a voice but involve no redistribution of the underlying power; in fact they may even consolidate underlying power imbalances by suggesting cohesion where inequality is rife.

One persistent challenge to pluralistic practices is how they are organized, recorded, and disseminated. Peer-reviewed academic articles are still the primary way in which practice is valued and consumed beyond a local level. This may exclude nonacademic participants or devalue nonacademic forms of communication. In her examination of archaeological forms of language, Rosemary Joyce (2002) uses Mikhail Bakhtin’s concept of “polyphony” to highlight the problems with many attempts to capture multivoicedness. In polyphony, multiple voices with their own autonomy and strength are engaged in an open-ended dialogue, but this is not always achieved in self-conscious attempts to co-opt other voices into archaeological texts.

The representation of multivocality to the public is not without its challenges either. Within heritage interpretation, the importance of participatory practice is recognized by professionals and funders, although the term multivocality is rarely

used. Multiple interpretive outcomes are used, with the medium chosen collaboratively, to suit the group in question. However, the style of representation may unintentionally marginalize or “mark” voices as unofficial. Permanent-looking text-based forms of interpretation, which obscure authorship through the use of the passive voice, may be seen as more reliable than creative or unorthodox forms of interpretation. Nonprofessionals may also actively adopt what they see as official forms of expression, out of a wish to legitimize their work or censor their own histories for an outside audience (Bender 1999).

Multivocality and pluralistic ways of working thus require relinquishing control while still trying to deliver shared outcomes. A research team needs to be self-critical and honest about failure and false starts, rather than shouting only about success stories. Taken to an extreme, this way of working involves an acknowledgment that nonarchaeologists are a part of the team and not just there to be consulted. This kind of archaeology is a challenging, messy, and iterative process of dialogue, participation, and experimentation; it is not a box-ticking exercise.

SEE ALSO: Archaeology and the Present; Authorized Heritage Discourse; Community Heritage; Experts and Stakeholders; Heritage: Nonwestern Understandings; Heritage and Community Archaeology; Heritage and Human Rights; Heritage and Politics; Heritage and Society; Heritage and Value-Based Approach; Heritage Ethics

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Public Archaeology

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For as long as there have been remains of past people and societies, there have been scholars and members of the public fascinated by these traces. Since the beginning of the discipline, archaeologists have found appreciative members of the public keen to see them work, hear them speak, and read their words. The foundations of public archaeology lie in the efforts of early archaeologists to encourage, shape, and exploit this widespread and intense popular interest. Today, public archaeology is a thriving subdiscipline that seeks to encourage, equip, and enable archaeologists to share their work with public audiences, while also turning a critical eye to the places where practitioner and public meet and interact. As archaeology has moved from the realm of the amateur into the more regulated worlds of government, industry, and academia, the need for communication and understanding across boundaries of public and private has become ever more clear and urgent.

The definition of public archaeology is hard to pin down, and due to the often very different national traditions of the term in the United Kingdom, the United States, and elsewhere it is perhaps better to speak of a cluster of definitions. It is important to note that most of the practices now included within the broad term public archaeology predate its first use by decades or even centuries. A book entitled *Public Archaeology* published in the United States by Charles McGimsey (1972) identified it as archaeology carried out by state and official bodies on behalf of the public, and this definition remains a central and important one, particularly in relation to the work of state and nonstate environmental, heritage, and landscape management bodies

such as the US National Park Service. State heritage agencies and related nonprofit and non-governmental organizations (NGOs) remain the principal employers, supporters, and funders of public archaeology around the world.

Due to the difficulty in defining public archaeology, scholars have tried to categorize and identify the main themes within the field. Drawing on concepts from the field of science communication, Merriman (2004) distinguished the “deficit model,” based on educating the public about archaeology, from the “multiple perspectives model” that encourages collaboration and co-creation. Okamura and Matsuda (2011) further divided this typology, noting that within the practice-focused dimension of public archaeology, which builds upon Merriman’s deficit model, there is both an educational dimension aimed at informing the public, and a public relations approach aimed at raising the profile of archaeology in the public sphere, including political lobbying in support of heritage protection. On the more academic side of public archaeology, they further identified a critical approach drawing on social theory that examines the place and function of archaeology in the real world, for example in relation to postcolonial and radical political movements, and a multivocal approach that focuses on exploring and promoting diversity and pluralism in the study and presentation of the human past. These studies of the nature of public archaeology are important in that they highlight the division within the discipline: on the one hand, public archaeology is a field of scholarship with an extensive and well-developed critical discourse; on the other hand, it is a profession based on the development and use of a distinct set of skills and expertise.

There is a long tradition of archaeologists communicating their work to the interested public through a variety of media. One of the earliest examples of this was Austen Henry Layard’s excavations at Nimrud in the 1840s which led to the publication of *Nineveh and its Remains* (Layard 1849), which linked Layard’s discoveries to biblical history and captured the public imagination.

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Between the nineteenth and twentieth centuries, coverage of archaeological work in popular outlets also helped to fund the excavations: Heinrich Schliemann wrote regularly for major European newspapers, while Howard Carter's work was closely followed by journalists.

Beside reading about archaeologists' work in the press and popular books and following the process on television, excavations themselves have attracted the attention of curious passers-by since at least the eighteenth century, when one British antiquarian described himself as "plagued" by interested locals, while Egyptologist Flinders Petrie famously dug wearing a flesh-toned outfit in the hope that his apparent nudity would deter visitors from approaching. Others were less reticent: the monumental excavations at Maiden Castle, Dorset, England in the 1930s saw director Mortimer Wheeler encouraging public visits, arranging tours and lectures, and selling artifacts and postcards as souvenirs. Since the 1980s, the large international research project at Çatalhöyük has explored different ways of including and engaging the different community stakeholders in their work, and, despite the emergence of new media, site visits and tours remain an important element of public archaeology.

Many of the practices of public archaeologists are also described under the term "community archaeology," and they are often used interchangeably (see *COMMUNITY HERITAGE* and *HERITAGE AND COMMUNITY ARCHAEOLOGY*). Community archaeology tends to refer to work that includes interested nonprofessionals in the archaeological process, including as excavators. One of the earliest and most remarkable community archaeology projects was the Tsukinowa burial mound excavation in Japan, begun in 1953. This project was led by academic archaeologists from Okayama University who aimed—drawing on explicitly socialist ideals—to include people of a wide range of ages and backgrounds in the excavation. Ultimately, more than 10,000 people took part, including archaeologists, teachers, students, and local people.

One of the most disconcerting parts of working in public archaeology is the discovery that most of the public obtain their understanding of archaeology and the work of archaeologists from a range of cultural references, ranging from the painfully outdated to the utterly deranged

(Holtorf 2005). The study of cultural representations of archaeology might seem like an excuse to read comics and watch movies, but it offers vital insights into popular engagement with the human past. Some argue that the high profile of archaeology in popular culture is largely a positive, while others raise concerns about outdated and potentially exclusionary stereotypes, which might ultimately harm the cause of public archaeology.

Historians of archaeology have highlighted the fact that many attempts at communicating archaeology to the public have been part of deliberate campaigns of nationalist propaganda (see *HERITAGE AND NATIONALISM*). In these cases, appeals to a shared, glorious ancient ancestry have been used to bind together a geographic population into a nation or people. The newly independent nation of Pakistan hired Mortimer Wheeler to present an ancient pedigree for a new country with his book *Five Thousand Years of Pakistan* (1950), while Southern Rhodesia renamed itself Zimbabwe after its most famous archaeological monument, taking its national flag and symbol from the carved stone bird artifacts found at the site.

The close connections between archaeology, nationalism, and colonialism saw a backlash in the 1980s, encouraged in part by the controversial first World Archaeological Congress in 1986. Members of indigenous populations and formerly colonized nations around the world demanded an ethical discourse in archaeology that recognized their cultural property and rights. In North America and Australia, these debates focused heavily on human remains held in archaeological collections and museums, and campaigns for their return and reburial led to the passage in 1990 of the landmark US Native American Graves Protection and Repatriation Act. In other cases, campaigns focused on the repatriation of stolen cultural objects from museums have been less successful, such as the requests that the British Museum return the Benin Bronzes to Nigeria; for some time there has been an intense debate in the museum world surrounding these issues (see *CRITICAL MUSEOLOGY* and *REPATRIATION*).

The looting of archaeological sites remains a lively issue in public archaeology, particularly in areas such as Italy and Egypt, where artifacts can reach high prices from unprincipled collectors.

The most vulnerable archaeological sites are those in conflict zones such as (at the time of writing) Iraq, Syria, and Yemen, often targeted for deliberate destruction. At the same time, looting archaeological sites can be an opportunistic crime by poor and vulnerable people looking for ways to survive. Ethical debates in archaeology are a central part of public archaeology discourse, and issues around the protection of heritage sites in conflict are some of the most salient and controversial. Should archaeologists work with military-occupying forces to protect cultural heritage? Should we turn a blind eye to looters who would otherwise be unable to feed their families? How do we value heritage compared to human lives? The debates around these questions where archaeology meets the rest of the world are at the core of contemporary archaeology (see HERITAGE AND HUMAN RIGHTS AND HERITAGE ETHICS).

Public archaeology is growing in several different directions, and the future of the field looks strong. The concept of “citizen science” is starting to affect our understanding of the roles that the public can play in archaeological work. Amateur archaeologists are monitoring the erosion of coastal heritage sites, reporting metal-detecting finds to national databases, helping to transcribe and digitize old archives, and engaging in conservation projects, in collaboration with academics, museums, government bodies, and heritage professionals (see RESPONSIBLE METAL DETECTING). One of the most powerful tools in this growth of public archaeology has been the use of digital resources, both as a means of sharing archaeological data with the public and as a way for the public in turn to add and contribute (Bonacchi 2012). Archaeologists are asking the public for help monitoring satellite images of endangered sites for signs of looting, while some remote or inaccessible excavations are providing webcams so that interested people all over the world can watch the work progress. Digital media are broadening-out public archaeology: where previously a few archaeologists might write for a popular audience, it is now far easier to disseminate information, including regular updates on work and discoveries. Museums and collections are also using digital media to open up archives that would otherwise remain hidden to visitors.

Public archaeology today is exploring new ways of using digital media in practice: one of the emerging challenges for public archaeologists is to maintain critical analyses of these digital encounters between the public and archaeology. Hopefully these new ideas and approaches to a well-established field will provide new contributions to the long-standing discourses around values, ethics, education, participation, repatriation, ownership, and identity.

SEE ALSO: Community Heritage; Critical Museology; Heritage and Community Archaeology; Heritage and Human Rights; Heritage and Nationalism; Heritage Ethics; Repatriation; Responsible Metal Detecting

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Re-Enactment and Engagement

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Re-enactment is a term covering a wide array of different activities related to the staging and animation of selected fragments of the past in the present. The re-enactment activities within archaeology and the heritage sector, typically performed by costumed participants (re-enactors) in front of an audience, are sometimes referred to as “historical” re-enactment in order to distinguish them from other disciplines’ use of the term and method. In film studies, theatre studies, and media studies, for example, “re-enactment” is generally used to describe the reviving or restaging of older pictures, formats, or events on stage or in front of the camera. Although there are overlaps, for example when filmic re-enactments include groups of historical re-enactors hired as extras, the present discussion concentrates on historical re-enactment as it is practiced within the heritage sector.

Typical examples include re-enacted battles and other pivotal events such as historical speeches, protest gatherings, marches, ship journeys, slave auctions, and courtroom sessions. While some reserve the term re-enactment strictly for those instances in which a precise historical moment is being restaged—for example, the 1620 landing of the *Mayflower* or the 1815 Battle of Waterloo—in its common usage it also covers more generic heritage or “period” activities, such as Viking or medieval markets, craft and culinary demonstrations, or World War II encampments and air shows. Some insist that such nonspecific elicitations should be labeled “living history” activities and not re-enactments.

It is common to view historical re-enactment and living history contexts as particularly accessible and engaging educational settings, catering to audiences unaccustomed to more conventional,

academic modes of appropriation. Proponents of re-enactment-based approaches stress the three-dimensional and multisensory quality of the experience, the possibility of dialogic engagement between re-enactors and audiences, and the chance to work physically and materially with historical or archaeological traces and theories—with implicit or explicit connections to the genre of experimental archaeology. Conversely, critics have pointed to the dangers of uncontrolled experimentation and play, conjectural dramatization, and the tendency among some re-enactors to focus heavily on material details (such as weapon types, uniform buttons, sewing styles) while ignoring larger historical or political contexts. In some cases, strong commercial and tourist-oriented agendas influence the alleged educational or scientific outcome. Indeed, this is a field in which a strict upholding of boundaries—for instance between entertainment and education, between the production and the consumption of heritage, or between experimental and experiential modes of engagement—can be very hard to control.

Historical context

Re-enactment is not new. In one form or another, the human need to narrate and perform “what happened” in other times to an audience is probably as old as humankind itself, and so are the surrounding debates about the historical accuracy of each new performance. In ancient Rome, imperial victories in faraway lands were often restaged for the public, including alleged cases of spectacular naval battles in which the Colosseum was flooded. In many religions, foundational stories and rituals have survived in forms with obvious re-enactment traits, such as the widespread Good Friday recreations of the Crucifixion of Christ, the Islamic *hajj* pilgrimages to Mecca, and Buddhist rites based on rigorous replication of ancient procedures. The proposed connections in such religious practices between

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corporeal imitation and inner experience can be likened to the strivings of modern re-enactors, who often claim to have been touched or moved by “history” through their bodily and material efforts.

During the late nineteenth century and early twentieth century, as new paradigms of exhibition and entertainment developed across the western world, the use of re-enactment-style demonstrations became increasingly popular. The World Fairs and Great Exhibitions of the period often included folk exhibitions in which “savages” and other colonial subjects were employed to typify “exotic” cultures under western domination, supporting the racialized hierarchies of the era. In the traveling Wild West shows, organized by entrepreneurs like William “Buffalo Bill” Cody from the 1880s onwards, key battles and episodes from the American Indian Wars were replayed in circus-like frameworks in which Native Americans performed as (stereotypes of) themselves. Meanwhile, the open air museum movement, emanating from Scandinavia in the same period, popularized exhibition principles known also from the World Fairs, including the idea of reconstructed “interiors” that could be manned with mannequins or, later, live people.

In 1920, in the recently formed Soviet Union, a grand re-enactment of the 1917 Storming of the Winter Palace in Petrograd (today’s St Petersburg) was staged, involving Vladimir Lenin himself. In turn, this simulation inspired key scenes of Sergei Eisenstein’s 1928 propaganda film *October*, which, over the years, came to be viewed in the USSR as the legitimate historical representation of the event. In twentieth-century the United States, the recurring anniversaries of the American Civil War, and especially of the (1863) Battle of Gettysburg, became key nodes for the development of re-enactment as a genre of mass commemoration. The fiftieth Gettysburg anniversary in 1913 was billed as a “reunion” between North and South, but it is the 1963 centennial that is usually seen as the birth of modern-era re-enactment. Today, besides the still popular American Civil War scene, major battle re-enactment societies include practitioners of Viking, Medieval, English Civil War, Napoleonic, and World War I and II history.

Appeal and engagement

The bodily, tangible, and interactive possibilities of re-enactment set it apart from most other kinds of engagement with historical material. Advocates of re-enactment and living history stress these qualities as fundamental to the method’s public appeal and the educational possibilities it holds. Even though most materials used for re-enactment are reproductions rather than original historical artifacts, the genre’s orientation towards haptic and tactile engagement makes it well suited to trigger debates belonging to a different register than those derivable from text- or exhibition-based learning. Immersing oneself in the restaging of past events may provoke questions of movement, posture, and emotion, potentially pushing the performer to reflect upon the past in a new light. Such kinds of engagement display obvious parallels with other phenomenological approaches in archaeology, in which subjective and experiential dimensions are accorded similar academic credence. Under the right circumstances, re-enactment sessions hold an educational value difficult to obtain through conventional learning. Indeed, several primary- and secondary-level educational programs make use of some variety of re-enactment, for example by training students to simulate and respond to historical events on the basis of prior reading of source materials.

Re-enactments, wherever they are performed, can never guarantee full historical accuracy or objectivity. Conditions are almost inevitably uncontrollable, and commercial, political, or other agendas threaten to obscure the relationship between the original event and its resurrection. Furthermore, although re-enactors are generally intensely preoccupied with “authenticity”—taking this ideal to entail, most often, a material and visual likeness of the past—it is rarely hard for critics to point out aspects not in accordance with the historical record. Given this impossibility of full historical perfection, one may seek to escape such an authenticity-bound framework by viewing re-enactment and its appeal in a different light: as a genre of historical commitment with the potential to facilitate a particular kind of resonance and sensitivity towards selected elements and conditions of the

past. Re-enactments, through their intentional reworking, can sometimes breathe new life into or challenge established understandings or cultural practices, and may also provide minorities or underprivileged groups with a voice in the telling and retelling of history.

Key debates and problems

The quest for authenticity, and the question of what one should take an “authentic” performance, battle, or object to mean in the first place, is a foundational debate among re-enactors. While it is obvious that there can be no full 1:1 resemblances between then and now, a strong urge towards getting “as close as possible” to something of “what it must have been like” remains the ideal. Some re-enactors speak of “magic moments” or “period rush”—flashes of time in which the barrier between now and then seems to break down and afford almost revelatory experiences. On a less subjective level, authenticity issues emerge constantly: for example, whenever decisions must be made as to whether or not certain textiles or uniforms can be allowed, whether one should speak in the first or the third person when addressing an audience, or when a particular battle scenario and its historical basis are discussed. Several commentators have sought to distinguish between different meanings of the notion of authenticity, to better grasp the assumptions and agendas underlying various invocations of the term.

Given that battle re-enactments constitute such a key part of the living history scene, the understandings and images of history ingrained in it have been accused of being militaristic, masculine-centered, and, in some cases, overtly patriotic or nationalist. It is surely the case that this is a male-dominated field driven by a passion for war history. Although quantitative data are scarce, most studies agree that re-enactment groups are dominated by participants with politically conservative stances. While it is undeniable that some re-enactment societies are saturated with right-wing attitudes—from American “Odinist” Viking groups to Russian “military-patriotic” youth educational camps—one should take care not to mechanically

equate re-enactment as a practice or method with orthodox ideologies. As a tool for engagement with the past, re-enactment has also been utilized to mobilize protest and the struggles of the weak, for instance in lynching scenarios performed in the US South and in revivals of the 1989 revolutionary marches across eastern Europe.

While some scholars uphold a critical view of re-enactment, stressing the risk of hollow, superficial, politically dubious, or commercialized performances, others have explored these phenomena for their performative and educational power and the ways in which they can provide individuals and groups with agency and resonance. These are also debates on authority and expertise; on whether the kind of visceral engagement with the past that re-enactment offers amounts to historical knowledge of a legitimate kind. In today’s experientially saturated cultural landscape, where many museums and other cultural institutions employ re-enactors and living history groups—many of whom are volunteers—these issues can be pressing. In some cases, especially when it comes to dealing with recent historical periods, they are entangled with complex ethical questions: Is it acceptable, for instance, to re-enact Nazi militarism or to flag the Confederate colors during a re-enactment of the American Civil War? Are performances to be likened to theatre plays, where re-enactors merely play “roles”—or are they also, in fact, political expressions of identification and sympathy? While participants will most often argue that they are simply performing historical episodes as faithfully as possible, re-enactments can be divisive rather than enlightening, especially in cases when accounts and facts are strongly contested. These questions keep sticking to the genre, especially in its military forms, testifying to the gray zone re-enactment inhabits in which personal incentives and identifications, playful leisure settings, and institutional or scientific interests intersect. They serve as a reminder that any reinterpretation of history, as it ascribes new meaning and power to the past, is always already infused with political positioning and thorny issues of representation.

SEE ALSO: Archaeology and the Present; Community Heritage; Embodiment; Experiment in Archaeology; Experts and Stakeholders; Making and Skill; Perception and Experience

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Repatriation

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Repatriation refers to the return to the country, community, or tribe of origin of cultural heritage and ancestral remains which were acquired by museums, collecting institutions, or private collectors prior to the introduction of heritage protection laws. Since the 1960s, it has become an international issue of significance to archaeology, anthropology, and museology because of efforts of nations and communities to reclaim items that were acquired by various means including plundering, looting, purchase, trade, and excavation.

Imperial expansionism was a primary mechanism for acquisition of vast collections of cultural materials now housed in museums in colonizing countries. Many repatriation claims relate to materials acquired during European colonization in the Americas, Australasia, Africa, and India, and Japan's colonial occupation of Korea.

Repatriation also relates to the return of antiquities that were acquired prior to heritage protection laws when nations permitted excavation of archaeological sites by researchers from overseas. Through a system of partage, archaeological teams were able to export a portion of collections to the museums, universities, or private collectors that funded the excavations, sometimes for a specified loan period. These were not always returned and so became the subject of repatriation claims.

The term restitution is used to refer to the return of materials that were taken illicitly after the introduction of national and international legislation to protect cultural heritage. In recent decades, many countries have introduced national legislation to prohibit looting and unauthorized exportation, which results in physical damage to monuments, as well as loss of the cultural heritage of descendant communities, and information of historical, scientific, and artistic importance. At an international level, the

United Nations (UN) adopted the 1970 UNESCO Convention on the Means of Prohibiting and Preventing the Illicit Import, Export, and Transfer of Ownership of Cultural Property. Efforts have also been made to establish international rules of war to protect cultural property in private homes, places of worship, and public institutions. Despite these efforts, monuments, museums, libraries, and archives in conflict zones continue to be targeted for looting or destruction and, with a highly lucrative international market for art and antiquities, archaeological sites across the world remain susceptible to looting.

While collectors, auction houses, and museums endeavor to establish accurate and legitimate provenance of potential acquisitions, verifying the past history of ownership is complex, made more difficult by falsified records created by unscrupulous dealers, and some museums have had to return purchased objects later found to have been looted and illicitly trafficked.

Human remains

Museum collections of human remains include ancient Egyptian and Peruvian mummies acquired through archaeological excavations and human remains collected during the eighteenth, nineteenth, and early twentieth centuries, primarily in North America, Australia, and Africa. They were collected by medical officers, military personnel, archaeologists, and anthropologists to be used for the study of ancient civilizations, burial practices, human evolution, migration patterns, and paleopathology. Historical records provide accounts by some collectors of theft of human remains and funerary objects from burial sites and shrines, the removal of bodies from sites of violent conflict, and body parts being collected by souvenir hunters (Fforde, Hubert, and Turnbull 2002).

Indigenous people have become increasingly vocal in their criticism of western science, research, and museum practices. In statements such as the *Kari-Oca Declaration*, *The Indigenous*

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Peoples' Earth Charter (1992), and the *Mataatua Declaration on Cultural and Intellectual Property Rights of Indigenous Peoples* (1993), indigenous peoples emphasized the diversity of cultural heritage, its importance to cultural identity and community well-being, the intangible and spiritual aspects of heritage, and the need for heritage protection. They asserted their cultural and intellectual rights as human rights issues, and appealed for protection of sacred and ceremonial sites, and repatriation of human remains, funerary objects, and sacred and ceremonial objects from museums.

Initially, western scientists and museums resisted repatriation claims, asserting legal ownership, the primacy of scientific research, and its importance to humankind; however, attitudinal changes and policy developments have occurred within the archaeology and museum sectors. Although the repatriation of human remains was—and to some extent remains—professionally divisive among scientists, a statement of principles was agreed by archaeologists and indigenous peoples at the World Archaeological Congress (WAC) in 1989. In 1990, the WAC adopted *Archaeological Ethics and the Treatment of the Dead* (the Vermillion Accord), requiring respectful treatment of the dead regardless of background or origin.

Domestic repatriation policy developments

Significant legislative and policy developments have occurred regarding repatriation in several countries, in most cases relating to the cultural heritage and ancestral remains of indigenous populations.

In the United States, the National Museum of the American Indian Act (1989) and the Native American Graves Protection and Repatriation Act (1990) were passed to protect Native American and Native Hawaiian ancestral remains, funerary objects, and certain categories of sacred and ceremonial objects, and establish the responsibilities of federally funded museums to source communities. These included generating inventories, informing communities of holdings, and responding to repatriation claims.

Guidelines for museums in Canada were introduced in 1992, although compliance was left

to individual museums to consider claims on a case-by-case basis. In March 2000, the Provincial Government of Alberta, Canada, enacted the First Nations' Sacred Ceremonial Objects Repatriation Act, providing a mechanism for unconditional repatriation of sacred and ceremonial objects from Glenbow Museum and the Provincial Museum of Alberta, if requested by bands of the Blackfoot Confederacy in Alberta.

In Australia, major Australian museums had ceased to display human remains or secret/sacred objects by the 1980s. The first repatriation of ancestral remains occurred in 1985, with the repatriation of the Murray Black collection from the University of Melbourne Medical School. In 1993, the Council of Australian Museum Associations (now Museums Australia) introduced guidelines relating to museums' relationships with indigenous communities and included recommendations concerning repatriation. Since then, the Australian government has funded the Return of Indigenous Cultural Property Program to support research and repatriation of secret/sacred objects in the collections of the eight national, state, and territory museums.

International repatriation

In Europe and Asia, most repatriation requests are initiated by indigenous communities in nations that were colonized or between countries that were occupied. After Greenland obtained home rule in 1979, the National Museum in Denmark (NMD) and the National Museum of Greenland agreed to split the collection of Greenlandic heritage held in the NMD and over 35,000 objects were repatriated to Greenland. Since 1983, the Greek government has been seeking the return of the Parthenon Marbles which were removed from Greece in the early nineteenth century during a period of Ottoman rule.

As a result of British imperialism, UK museums hold vast collections of antiquities, ethnographic materials, and human remains from around the world. Indigenous peoples overseas have sought the repatriation of human remains and cultural materials originating from North America, Australia, and New Zealand. The return of other significant items of cultural

heritage is being sought by governments of former British colonies: the Koh-i-noor diamond (India), the Benin bronzes (Nigeria), and the Rosetta Stone (Egypt).

In 2000, the UK Museums and Galleries Commission introduced *Restitution and Repatriation: guidelines for good practice* relating to cultural objects. Guidelines for the treatment of human remains in museums in England, Wales, and Northern Ireland are provided by the Department for Culture, Media and Sport's *Guidance for the Care of Human Remains in Museums* (2005), and in Scotland by Historic Environment Scotland's *Treatment of Human Remains in Archaeology* (2006) and Museums Galleries Scotland's *Guidelines for the Care of Human Remains in Scottish Museum Collections* (2011).

In 2013, the German Museum Association introduced *Recommendations for the Care of Human Remains in Museums and Collections*. As in Britain, these are intended to guide museums in the establishment of institutional policies.

In France, another major colonizing power, legislation was passed in 2002 and 2010, but this is limited to specific cases of repatriation of human remains to South Africa and New Zealand.

The US Department of the Interior has established a Working Group for International Repatriation of Native American Cultural Heritage to assist Native American tribes seeking assistance with repatriation of stolen, looted, or trafficked cultural heritage in museums and auction houses overseas.

The Australian government's Indigenous Repatriation Program, operated by the National Museum of Australia, assists with the return of Aboriginal and Torres Strait Islander ancestral remains from Australian and overseas museums.

The International Council of Museums (ICOM) Code of Ethics for Museums (2013) provides guidance in all aspects of museum practice including repatriation and restitution, and forms the basis of the Code of Ethics of many national museum organizations and the repatriation policies of individual museums.

Nevertheless, some of the world's major museums remain resistant to repatriation claims. In 2002, directors of 18 museums in Europe and North America signed a *Declaration on the importance and value of universal museums*, arguing

that the importance of their collections for comparative research into technological, stylistic, and artistic expressions across temporal and cultural boundaries overrides claims of source communities or nations.

Conventions adopted by the UN call for protection of cultural heritage in all forms, including intangible and spiritual heritage, and reference indigenous custodianship of human remains and sacred and ceremonial objects as human rights issues. The rights of indigenous peoples were affirmed in the *Declaration on the Rights of Indigenous Peoples* (2007) and the *World Conference on Indigenous Peoples Outcome document* (2014), exhorting States to develop mechanisms to facilitate access to and repatriation of ceremonial objects and human remains at national and international levels. In 2015, the United Nations Human Rights Council (UNHRC) called for museums and other places holding collections to "inform the relevant indigenous peoples and develop mechanisms to facilitate the return of such cultural heritage when sought by the indigenous peoples concerned" (UNHRC 2015). The United Nations Permanent Forum on Indigenous Issues (UNPFII) recommended that States and indigenous peoples "establish a working group to prepare a manual of good practice with regard to the repatriation of ceremonial objects and human remains" (UNPFII 2015).

Repatriation and its outcomes

Repatriation negotiations can lead to the establishment of collaborative relationships benefiting both museums and communities. The return of archaeological artifacts to Peru from Yale University in 2012 included a partnership agreement with the Universidad Nacional de San Antonio Abad del Cusco (UNSAAC) in which a new Center for the Study of Inca Culture would be established in Cusco to store and display the collection under a shared stewardship arrangement.

Since the late 1990s, the Haida community in British Columbia, Canada, has negotiated the repatriation of the remains of several hundred



Figure 1 Haida repatriation ceremony, 1998. Skidegate community members carrying boxes of ancestral remains from canoe on beach to Skidegate Community Hall.

Source: Haida Gwaii Museum, Canada, published with permission.

ancestors from North America museums, forming positive working relationships with some. Ancestral remains were repatriated and reburied in painted bentwood boxes made using traditional methods relearned from examination of examples in museum collections (Figure 1). In recent years, the Haida Repatriation Committee has reached out to museums in the United Kingdom, leading to collaborative projects with the Pitt Rivers Museum and the British Museum (Krpmotich and Peers 2013).

In Alberta, Canada, the Kainai (Blood Tribe of the Blackfoot Confederacy) had been seeking the return of medicine bundles since the early 1970s. During the 1990s, Glenbow Museum in Calgary and the Provincial Museum of Alberta in Edmonton were lending sacred bundles to Blackfoot ceremonialists for use in ceremonies essential to the continuation of Blackfoot world views. Through relationships built over a number of years, museum staff developed greater insights into cultural and ceremonial life and the importance of the bundles, and produced collaborative exhibitions with the Blackfoot communities. In January 2000, 251 artifacts, including a number of ceremonial bundles, were transferred

unconditionally from Glenbow Museum to the Blood, Peigan, and Siksika communities.

SEE ALSO: Heritage: Nonwestern Understandings; Heritage and Conflict Resolution; Heritage and Human Rights; Heritage Ethics

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Responsible Metal Detecting

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Among the different forms of artifact hunting, hobbyist metal detecting has been of particular interest in recent years to researchers, especially in regions such as northern Europe where metal artifacts are in relative abundance and where laws do not prohibit metal detecting. Countries that have fuller restrictions, such as Cyprus (Hardy 2014), often also have more extensive state intervention regarding cultural heritage in general, such as the state ownership of cultural objects, or have experienced an incident that has affected opinion concerning the acceptability of metal detecting as a hobby, as with Ireland (Kelly 1993).

Metal detecting emerged as a hobby in which members of the public could partake, in countries such as the United Kingdom and the United States in the 1960s, although metal-detecting devices—originally developed in the military for mine searching—had been available before then. There is evidence of archaeologists trying metal detectors in the mid-twentieth century, such as in England in 1948 (Hobbs 2003, 18) and the United States in 1958 (Connor and Scott 1998, 76).

Despite early tests of the efficacy of metal detectors as archaeological survey tools, the devices have attracted controversy, especially in the 1970s and 1980s, with the rapid growth of hobbyist metal detecting (Thomas 2012). Incidences of looting using metal detectors, as well as tensions around the different ontologies adopted by archaeologists and other heritage professionals, and within the metal-detecting community itself, have led to conflict at different times, sometimes spilling over into broader political debates about heritage management policy.

In some countries, such as Sweden, Russia, and France, it is illegal to metal detect. This does not necessarily prevent looting, which is still a problem in many places where metal detecting

is not permitted. Some countries, such as Estonia, permit metal detecting provided the metal detectorist has applied, and fulfilled the criteria, for an official license. In other countries, such as Denmark and the United Kingdom, metal detecting is legal in many circumstances (although certain areas of land may be protected, for example if designated as a site of archaeological significance). In situations where metal detecting is permitted, hobbyists are nonetheless required to meet their legal obligations: in most cases, including New Zealand and Finland, hobbyists should not disturb known archaeological sites, and in many countries there are various levels of mandatory reporting of finds. Furthermore, the use of metal detectors in a hobbyist capacity not only relates to the search for archaeological material: Internet discussion forums in Australia and New Zealand indicate that gold prospecting is a major goal of hobbyists in those countries, for example. The legal requirements for finds recording thus vary from jurisdiction to jurisdiction, although responsible metal detectorists would be expected to report not only the objects that the law requires them to report, but also other archaeological and historical material.

Beyond often basic legal requirements, it is clear that the practices of hobbyist metal detectorists put many more objects of archaeological significance at risk. Therefore, in many jurisdictions where metal detecting is permitted, hobbyists are also encouraged to practice their hobby responsibly, to ensure that more archaeologically useful information can be gathered from their discoveries. Critics of metal detecting argue that the removal of objects by untrained detectorists cannot ever be at a standard comparable to that of a scientific investigation (e.g., Gill 2010); others have acknowledged that in certain circumstances—such as areas where land has already been plowed or otherwise disturbed—and with a responsible approach, it is still possible to salvage scientifically useful information (e.g., Kershaw 2013).

Responsible metal detecting is generally interpreted as the behavior, or best practice, of metal detectorists who adhere to a set of standard

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procedures to ensure that the archaeological context of what they find is adequately and accurately recorded, and reported to the correct authorities. This may mean reporting to a local or national museum, a national heritage authority, or other organization with designated responsibility for recording finds, depending on the country or region. There are also legal restrictions on the movement of certain cultural objects across national borders, which may affect detectorists who practice their hobby in more than one country.

In England and Wales, mandatory reporting is limited only to a few categories of finds that are defined as “treasure” in the Treasure Act 1996. Since 1997, this law has been complemented by the Portable Antiquities Scheme (PAS), which began as a pilot project in six regions and was later rolled out across the whole of England and Wales. Various organizations—representing both archaeologists and metal detectorists—have contributed to and shared a Code of Responsible Metal Detecting, which was agreed and published in 2006 and updated in 2017 (<https://finds.org.uk/getinvolved/guides/codeofpractice>), and the PAS maintains a network of Finds Liaison Officers to whom detectorists are strongly urged to report finds of all types of archaeological artifacts so they can be identified and recorded scientifically. Among the ways to be “responsible” according to the Code are “[r]ecording findspots as accurately as possible for all finds (i.e. to at least a one hundred metre square, using an Ordnance Survey map or hand-held Global Positioning Systems (GPS) device) whilst in the field.” If it appears that the discovery is something more significant than a stray find—such as a hoard of artifacts or possible part of an archaeological site—metal detectorists should refrain from further excavation and contact the heritage authorities.

Many organizations also offer advice to metal detectorists on how best to conserve their finds. The crucial element of accurately recording finds with an archaeologist, as well as refraining from “cleaning” the artifacts (which will remove further contextual information from the object), has led in recent years to various countries developing their own digital databases specifically for handling the finds data that metal detectorists and other artifact collectors have available. In addition

to PAS, which began its activities in 1997 in England and Wales and has curated a finds database from its outset, in recent years databases have come into development for Flanders, Belgium, the Netherlands, and Denmark. Several other European countries are in the process of developing proposals for finds recording schemes, and there are also discussions underway in some US states for state-wide recording schemes.

In addition to “responsible” behavior—meeting minimum standards in recording, conserving, and reporting their finds—Shott and Pitblado (2015, 12) have suggested that there are also “responsive” collectors (including detectorists) that have the potential to act responsibly, pending being made aware of how their collecting activities relate to archaeological practice: “We believe that collectors who meet these minimal standards are responsible, and those who might meet them after being educated are responsive.” Therefore, while some metal detectorists may currently not be practicing their hobby in a way that makes a significant contribution to archaeological research, they may nonetheless be receptive to encouragement to metal detect in a more responsible manner, by way of advice, outreach education, and training. In Scotland, a recent series of posters and leaflets published by the Scottish Treasure Trove Unit appears to have encouraged improved finds reporting from metal detectorists and others, by highlighting what kinds of objects from different historical and archaeological periods are of interest to the Unit, and giving visual representations of how such objects typically look.

Future research around the theme of hobbyist metal detecting and its impact on archaeology seems to be developing in a number of different directions. Although much research about hobbyist metal detectorists has already taken place within national contexts—notably in the United Kingdom but also elsewhere—there is arguably a need for a yet deeper understanding of the motivations of the hobbyists themselves, which in turn may assist strategies intended to promote and encourage responsible behavior. Unlawful metal-detecting activities also continue to be a cause for concern, for example operating metal detectors in jurisdictions where it is not permitted, or not having a license in countries where it is a requirement to have one, as well as looting

archaeological sites for saleable objects. In many cases, understanding the scale of these issues is impeded by a lack of robust data—exacerbated by the clandestine nature of many of these activities.

Research projects—including doctoral dissertations but also larger-scale studies—are increasingly making use of metal-detected data. This has led to the discovery of new artifact types, studies of finds distributions over landscapes, and even identification of previously unknown or not located battlefield sites and other categories of site previously less well documented. As more digital finds databases develop, there will be challenges to ensure that these digital data are compatible across databases and systems, in order to enable and enhance transnational research questions. In addition, ethical challenges within digital finds recording include providing open-access data to researchers from within and outside of institutional academia, without compromising the security of findspots and sites: Vulnerability to looting is a serious issue to consider. Because of this, restrictions are sometimes placed on the details regarding finds location that individual users are able to access. Opportunities for research using finds databases that share information provided by metal detectorists appear to have the potential to develop further research questions and projects to utilize these “big data” as they become more readily available and accessible.

SEE ALSO: Archaeological Record; Community Heritage; Ethics in Conservation; Experts and Stakeholders; Heritage and Community Archaeology; Heritage and Policy; Heritage Ethics; Heritage Management; Public Archaeology

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FURTHER READINGS

Value or Significance

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Heritage, conservation (see CONSERVATION), and cultural resources management (see CULTURAL RESOURCES MANAGEMENT) all involve taking action to prolong the life of something that might otherwise be lost, and that urge to take action is rooted in our perceptions of value or significance. The challenge is how do societies articulate that value and significance, who has authority so to do, and how, having articulated it, is it then managed?

While there are many different ways by which people identify and seek to sustain things that have value to them, this entry focuses on the articulation of value and significance in four areas: the formal designation of heritage sites; managing heritage; policy and advocacy; and heritage institutions.

Ideas about value have always underpinned laws to protect heritage, from the earliest medieval legislation on treasure to current laws (Carman 1996). However, it has only been since the 1990s that a more explicit understanding of value has sat beside the consideration of technical issues in heritage practice. Many of the heritage charters that guide heritage decision making in a European context, such as the 1931 Athens Charter for the Restoration of Historic Monuments, make brief references to value in decision making, but the 1979 Burra Charter (Australia ICOMOS 2013) was the first charter to be explicit about how an understanding of value can shape the way in which places are managed. The 2005 Faro Convention (see FARO CONVENTION) takes this a step further, by defining cultural heritage as inherited resources that reflect constantly evolving values, beliefs, knowledge, and traditions. The convention also touches on other kinds of value for heritage, including economic utility, and notes the importance of ethics in heritage practice.

Significance and value in designating heritage

The basis for formally protecting heritage sites or buildings is their collective value to people. Historic buildings and sites, including national parks, are “designated” when they are placed on a public list, schedule, or register, and that designation is recognized in law or public policy. Like other environmental constraints, heritage designation may bring benefits or restrictions for owners, which is why such lists and the criteria on which they are based are made public.

The criteria for designation are usually based on significance, which can be broken down into two elements: value (the different reasons why something is important to people) and significance (more strictly, the degree or level of that value, e.g. national importance). For sites and buildings, those values might include:

- historical interest, including association with events or significant persons;
- social or communal value;
- archaeological or evidential value—things that yield (or have the potential to yield) important information about the past;
- aesthetic (or artistic or architectural) value;
- scientific value, which may include natural heritage values;
- spiritual or symbolic value.

For conservation areas, and historic or cultural landscapes, the “special character” may be defined more widely to include issues such as identity, distinctiveness, or current uses. Sometimes cultural heritage is protected by its inclusion in natural heritage or other landscape designations.

Special interest or value need not be comfortable—sites of conscience, battlefields, and war memorials may be retained because they commemorate places of conflict and all reflect difficult historical events. The values of particular cultural groups may also be recognized; for example,

Australian federal legislation protects objects or areas of significance to Aboriginals in accordance with Aboriginal tradition.

To meet the criteria for heritage designation, sites also need to be shown to demonstrate a degree of significance that is commensurate with the weight given to preserving them in wider decision making. World Heritage Sites must be of “Outstanding Universal Value” to justify protection, and ancient monuments in the United Kingdom must be of “national importance,” whereas local heritage might simply require evidence to show that it is of local or state significance.

Advice on what to designate and why is usually provided by specialists, including anthropologists and archaeologists or indigenous community representatives, reporting in turn to an elected and publicly accountable local council, state, or national government body. Many jurisdictions allow for public consultation prior to or during the designation process, but ultimate accountability for what is protected usually lies with elected representatives.

The practical difficulty with formally protecting heritage places on the basis of their value is that perceptions of value are not static, but change with time and also in relation to other factors such as knowledge, one’s own cultural or community affiliations, and wider social, economic, and environmental issues. Sometimes they are only expressed in relation to a threat—such as a new development that might destroy cultural heritage.

Values in heritage management

Value and significance play a critical role in many of the legal, financial, and policy tools used to manage heritage places after they have been designated, such as planning policies and local plans, consent regimes, financial incentives such as tax breaks and grantaid, and management agreements (see *HERITAGE PLANNING AND DESIGN*). For publicly accessible sites, these might include park management policies, conservation management plans, heritage impact assessments, and archaeological evaluations, as well as ways of engaging with the public, including interpretation, marketing, and public programs.

As part of the process of publicly accessible sites, there is often an opportunity to explore

value in a more creative and nuanced way than is possible in the designation process. Understanding community and social values and the values of different users is often key to successfully sustaining a site (see *HERITAGE AND SOCIETY*). Equally, when dealing with proposals to change or demolish heritage sites in the planning system, heritage values need to be reconciled with other public benefits. The loss of valued heritage through development, for example, may be mitigated through an archaeological excavation that provides a public benefit by sharing knowledge.

Community engagement, mediation, and conflict resolution are increasingly important in managing heritage sites where there may be a wide range of different conflicting values (see *PLURALITY AND MULTIVOCALITY*). Heritage specialists may have a key role in helping to facilitate those conversations; alternatively, where heritage is one of many different environmental or social considerations, such as in considering new infrastructure or major developments, heritage specialists may have a more limited role.

Values in advocacy and policy development

Another kind of value arises from the benefits that flow from caring for heritage. Understanding these is of immense help in developing policies, in advocating for heritage protection, and in understanding the impact of future developments. Sometimes described as public benefits or instrumental values, these include:

- *Economic benefits:* Investing in or protecting heritage may generate new jobs or local investment. The value of private property in or near protected areas may also increase as a result of a higher quality local environment.
- *Social benefits:* Connecting with heritage or taking part in heritage activities, such as volunteering on an archaeological excavation, can provide people with new social relationships, new skills and confidence, intergenerational connections, and a greater sense of identity and inclusion; knowledge and information about the past can also be a social benefit.

- *Health benefits:* The experience of visiting sites or participating in heritage activities can bring physical and mental health benefits.
- *Environmental benefits:* Protecting heritage can deliver environmental benefits for habitats and species, as well as reductions in greenhouse gases and waste through retaining existing buildings.

These are also potentially matched by disbenefits. Owners may suffer economic harm through restrictions on development opportunities; there may be social harm where the values of certain groups are ignored or downplayed and people feel excluded; and there may be environmental harm where older buildings perform poorly in terms of thermal efficiency.

Such values can be captured through social, economic, and environmental research, including economic techniques such as “willingness to pay” surveys that monetize perceptions of value, social research into individual and group attitudes, or research into the performance of different building materials.

Ethics and values in institutions

A third kind of value is expressed through the way in which heritage specialists and organizations do business.

Caring for heritage almost always involves dealing with conflicting values, whether between different communities or different kinds of heritage, such as natural and cultural heritage. Conflicts of interest also arise in negotiating between development and preservation. Therefore, most heritage disciplines or professional groups, including archaeologists, have ethical principles or codes of conduct that govern the way in which members behave, particularly when working with groups who have different cultural values, or with antiquities which may be looted.

Equally, heritage organizations need to be able to demonstrate that they are transparent, fair, and accountable in the service that they provide to the public, in the use of public money or donations, and in the decisions that they make. Such values may be demonstrated through mission statements or codes of conduct, and in the case of larger organizations may be audited.

Debate

The articulation of value and significance in heritage has historically been grounded in the academic disciplines of archaeology, art history, social anthropology, architectural and design history, histories of technology, landscapes, and historical geography. To these have been added the expertise of people who have direct cultural associations with places, including Native American groups, first peoples, and aboriginal groups. In response to the need to work with more diverse concepts of value, heritage specialists are also turning to more collaborative techniques for exploring value, ranging from consultation and community engagement through to co-production, mediation, and conflict resolution (Myers 2016).

However, because protecting public heritage involves a process of selection, there is inevitably debate over what, why, how, and by whom things are selected. The field of “heritage studies” provides critical commentary on the way in which value is articulated, noting that heritage itself is a fluid concept. The work by Graham, Ashworth, and Tunbridge (2000) is one of several studies that chart the uses of heritage, reminding us that the values that underpin the selection of heritage sites are often rooted in wider political and social movements, such as the European nationalist movements of the late nineteenth century. Value-based heritage practice (see HERITAGE AND VALUE-BASED APPROACH) has also been criticized for objectifying and fixing certain values through categorization, and for the historical predominance of archaeological and aesthetic value over social value in assessments of significance (Jones 2017).

The study of how people value things is not just the preserve of heritage disciplines—economic models of value have dominated the field, supplemented by the recent subdisciplines of environmental, cultural, and heritage economics. However, environmental psychology, philosophy, social anthropology, and conflict studies can provide alternative perspectives on the way in which people value places and things. There are also a range of intellectual frameworks for conceptualizing value used by public policy makers to assess the benefit of intervention, including ideas

about well-being, public value, and sustainable development.

The need to reconcile a wide range of often-competing values, and the potential harm that can be done when people's values are not acknowledged, is what makes heritage management so complex and potentially divisive. Understanding and articulating value has become a central part of current practice, but the whole process of doing so is fraught and open to challenge, which is why ethics, community engagement, and the way in which value is captured and articulated has become as much of an issue for practitioners as core technical skills.

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FURTHER READINGS

World Heritage Sites Designation

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UNESCO's flagship: the 1972 World Heritage Convention

The “Convention Concerning the Protection of the World Cultural and Natural Heritage” (World Heritage Convention) was adopted by the UNESCO General Conference in November 1972. It has become the most widely recognized of UNESCO's cultural conventions, and is often referred to as UNESCO's flagship due to the prestige associated with the World Heritage List.

Amid growing concerns about the vulnerability of important places due to the effects of globalization and environmental impacts, the Convention's intent was to facilitate collective action in the face of these pressures. Like the idealistic universalizing mission of UNESCO (“building peace in the minds of men and women”), the World Heritage Convention is based on the presumption of a shared heritage. The loss of natural and cultural properties that transcend their local contexts is therefore detrimental to humanity as a whole, and the World Heritage List was established to designate properties of “Outstanding Universal Value” (OUV).

Implementation of the World Heritage Convention commenced in 1975. Entries to the World Heritage List began in 1978, with the first 12 properties inscribed from Canada, Ecuador, Ethiopia, the Federal Republic of Germany, Poland, Senegal, and the United States. Since then, the List has grown beyond the expectations of those who negotiated the Convention text (Cameron and Rössler 2013), and now consists of more than 1,000 individual properties (many of which consist of large areas of land, or contain several or even hundreds of individual sites). World Heritage properties range from single sites

to historic city centers, large landscapes, national parks, and transcontinental cultural routes.

There are currently 193 States Parties to the World Heritage Convention, bringing it to near-universal participation. The World Heritage Committee comprises 21 member states elected by the General Assembly of States Parties. The UNESCO World Heritage Centre (<http://whc.unesco.org/>) acts as the secretariat to the World Heritage Committee. Three Advisory Bodies formally contribute to the work of the World Heritage Committee, providing advice based on technical expertise: the International Union for the Conservation of Nature (IUCN), the International Council on Monuments and Sites (ICOMOS), and the International Centre for the Study of the Preservation and Restoration of Cultural Property (ICCROM).

Key concepts and processes

It is often assumed that UNESCO selects properties for inclusion in the World Heritage List, but only States Parties (national governments) can submit nominations. The nomination requirements are substantial, and the process is a significant undertaking for governments and associated communities.

The processes of nomination, evaluation, and inscription in the World Heritage List are detailed in the “Operational Guidelines” (UNESCO 2017). These have been revised more than a dozen times as the processes and concepts have evolved. The current version is 175 pages long, and additional guidance materials have been provided to assist users in navigating the requirements (for example, UNESCO 2011).

Each State Party is required to maintain a Tentative List, containing information about properties it plans to nominate to the World Heritage List in the future. A property must be included in the Tentative List for at least one year before it can be nominated.

“Outstanding Universal Value” (OUV) is the threshold and the conceptual centerpiece of

World Heritage, often described as “slippery,” evading precise definition (Labadi 2013). It is described as “cultural and/or natural significance which is so exceptional as to transcend national boundaries and to be of common importance for present and future generations of all humanity” (UNESCO 2017, par. 49). Nominations to the World Heritage List must articulate the case for OUV according to one or more of ten criteria. Nominated properties must also meet the qualifying conditions of integrity and authenticity (the latter for cultural properties only); and must have adequate legal protection and management. Community involvement is encouraged, and traditional management can be recognized. A boundary must be clearly delineated, and a further area—known as the “buffer zone”—is often established to provide additional protection for the setting of the property.

Inscription decisions are taken by the World Heritage Committee following evaluations by the IUCN (for natural values) and/or ICOMOS (for cultural values). The IUCN and ICOMOS consult relevant specialists within their networks: For example, for archaeological sites, the International Committee for Archaeological Heritage Management (ICAHM) provides input. The Advisory Bodies send a technical evaluation mission to visit the property during the evaluation process, and convene expert panels to formulate the recommendations presented to the annual session of the World Heritage Committee. The sequence of the evaluation work of the Advisory Bodies is outlined in Annex 6 of the Operational Guidelines (UNESCO 2017).

The World Heritage Committee does not always follow the recommendations of the Advisory Bodies, and the annual sessions can be the focus of considerable advocacy, media attention, and debates, both inside and outside the formalities of the meeting (Meskell and Brumann 2015). Because nominations are resource-intensive for the States Parties and involve the deployment of considerable political capital, the World Heritage Committee encourages “upstream” processes, drawing on the early advice of the Advisory Bodies so that there are fewer nominations that “experience significant problems during the evaluation process” (UNESCO 2017, par. 122). Typically, the inscription of a property on the

World Heritage List is the culmination of years of work for many people, and is joyfully celebrated.

Once inscribed on the World Heritage List, the State Party is responsible for the long-term protection, conservation, and presentation of the property. Monitoring the implementation and effectiveness of management and protection is therefore centrally important. States Parties are required to contribute to Periodic Reporting (approximately every six years). Where new developments and pressures are identified by the States Parties or civil society, State of Conservation reports can be requested and considered by the World Heritage Committee. In many cases, a Reactive Monitoring Mission, comprised of representatives of the Advisory Bodies and UNESCO, is invited to visit the property to better understand the issues, and to assist with the development of strategies for reducing the pressures and strengthening conservation.

In situations where the state of conservation is threatened by serious existing (“ascertained”) or potential pressures, the World Heritage Committee can include the property on the List of World Heritage in Danger. This decision is not taken lightly. States Parties often resist the application of this mechanism, considering it to be a sanction or criticism, even though the Convention established Danger Listing as a means of enhancing cooperation and resources where most needed. The “desired state of conservation” needed to remove a property from the Danger List is determined, along with relevant measures. The frequency of monitoring is increased for these properties, but it is nevertheless common for properties to remain designated in this way for long periods, due to the complexity and severity of the pressures. In rare instances, where it is determined that the OUV has been lost, the World Heritage Committee can remove properties from the World Heritage List. To date, this has occurred only twice, with the delisting of the Arabian Oryx Sanctuary in Oman (2007) and Germany’s Dresden Elbe Valley (2009).

Twenty-first-century tensions

World Heritage has been a focus of the emerging academic field of critical heritage, and has been analyzed by academic researchers from various

disciplinary perspectives (Meskell and Brumann 2015). The universalizing conceptual framework has been characterized as an authorizing discourse (see *AUTHORIZED HERITAGE DISCOURSE*) that privileges the role of experts and western notions of tangible heritage.

The Eurocentric conceptual framing of the Convention emerged as a tension at an early stage, but remains a pressing concern due to various entrenched gaps and imbalances in the World Heritage List. For example, the UNESCO region of “Europe and North America” accounts for close to half of the List. Since 1994, efforts to address these issues have been advanced by the “Global Strategy for a Representative, Balanced, and Credible World Heritage List,” including revisions to the criteria for inscription to reflect diverse understandings of heritage (Jokilehto 2008). Cultural diversity and inclusion remain unresolved points of tension; and “OUV,” “authenticity,” and “integrity” are contested concepts (Stovel 2007; Labadi 2013).

While the World Heritage Convention is praised for bringing the protection of natural and cultural heritage together in a single international instrument, World Heritage practices have demonstrated a clear segregation between them. Properties can be recognized for both cultural and natural values (“mixed” properties), yet these are relatively rare, and there are many more cultural than natural properties in the World Heritage List. In 1992, the introduction of “cultural landscapes” (the combined works of nature and humanity) sought to blur the nature/culture divide, but these are evaluated using the cultural criteria.

The definitions of “natural heritage” and “cultural heritage” are an obstacle for non-western cultures that view nature and culture as inseparable. Requirements for the “Free, Prior, and Informed Consent” of associated indigenous peoples were incorporated into the Operational Guidelines in 2015, and the articulation of rights-based approaches (see *HERITAGE AND HUMAN RIGHTS*) has accentuated the need for mechanisms within World Heritage that move beyond the separate nomination, evaluation, and protection of “nature” and “culture.”

The ballooning size of the World Heritage List and expanding notions of “heritage” have created

diverse notions about what constitutes protection and conservation, and increased interest in the discourse of sustainable development (see *HERITAGE AND SUSTAINABILITY*). Climate change, poverty, infrastructure, and rapid urbanization often factor in the state of conservation of listed properties.

Tourism interest and development can follow World Heritage listing (see *ARCHAEOLOGY AND TOURISM*). The economic potential of tourism is often evident in the motivations for seeking World Heritage designation. However, the pressures on World Heritage properties can be exacerbated by poorly managed tourism, which can also have the effect of displacing local people and/or their traditions and livelihoods. Managing the development of tourism infrastructure and the flows of benefits is therefore central for many World Heritage properties.

The World Heritage system establishes what has been termed a “three-legged stool”—States Parties, the World Heritage Committee, and Advisory Bodies—and its stability relies on each of these structural components to function effectively. Today, this metaphor is complicated by perceptions of increased politicization of decisions and opportunities for cultural diplomacy. The centrality of the state and the role of experts create obvious points of potential tension for local communities because applying OUV can filter out important local associations and traditions. The requirements for community involvement and consent are only generally described; and reports from media, professional organizations, and academic studies contain many cases where the outcomes of World Heritage for local people have been confusing or detrimental to their livelihoods, cultural practices, or self-determination. Yet there are other examples of proposals developed by communities themselves in “bottom-up” processes, suggesting promising possibilities for the future designation of World Heritage Sites.

SEE ALSO: Conservation Plans; Experts and Stakeholders; Heritage and Nationalism; Heritage and Politics; Heritage and Value-Based Approach; Heritage Management; Value or Significance

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Adobe

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The word adobe is described as a sun-dried mud brick. The use of these blocks to construct floors, walls, arches, and vaults is called adobe construction system. Adobe has been highly valued by many societies around the world because of its bioclimatic efficiency in cold and hot, arid, and humid regions.

The name adobe has its origins in the Spanish language and derives from the Arabic term “ottob” which means brick. Even though the word employed was documented in Spain in the twelfth century, it was not published in a dictionary until 1726 (Caro 1998).

However, the use of this construction system logically precedes by several thousand years the spread of its Castilian name. In the Middle East, archaeological evidence of its use has been found dating back to 8000 BC (Houben and Guillard 2001). The extensive diffusion of this building technique lies in the simplicity of mud brick manufacturing, storage, and construction. The survival of this traditional knowledge constitutes a fundamental source of information to be applied in contemporary sustainable construction.

The expression “adobe” is used erroneously as “mud” or unbaked earthen building systems. Previous research related to the origin and development of adobe presents multiple loopholes, mistakes and inconsistencies. Some of these derive from the names given to construction elements and typologies (Bardou and Arzoumanian 1981).

Adobe buildings consist of an elaboration of earth blocks that are shaped with adequate dimensions for ease of sun drying transport, and stacking. These units are stacked and laid in mud mortar in alternating course work, similar to the

technique used in masonry to place bricks or dressed stone.

Adobes have different forms and dimensions, ranging from hand-shaped amorphous types to those made with a shaped rigid mold. In some locations, it is possible to follow the evolution and the morphology of early adobes beginning with those presenting flat-convex forms obtained from the placement of mud balls on the ground, up to parallelepiped blocks with an elongated rectangular shape that are most common around the world.

Sphere-like, cylinder, conic, trapezoidal shape adobes exist, as well as special units designed for ornamentation purposes. Baskets or boxes made of reed were used to manufacture blocks. The rectangular shaped adobes made with wood molds constitute the peak of the adobe technology and evolution of the geometric form, remaining unaltered for thousands of years, as can be seen today. The geometry of these rectangular forms with a thickness equivalent to approximately one quarter of its length allows for different types of coursing and permits a rapid drying of the units that can be stacked on edge so its hardening becomes homogeneous (Fathy 1973).

The logic of the construction system is dictated by a careful size and handling of the units, as well as its production. This guarantees quality control in coursing and building profiles. Even though adobes of a larger size allow for less units per course, this could delay the construction due to the effort needed to mobilize heavier blocks. This is why, even without an existing “international standard,” the rectangular adobes in most of the world have dimensions between 16 and 32 inches in length, 8 and 16 inches in width, and 4 and 6 inches in thickness so that the total weight could be handled by one builder.

The soil to make adobe is extracted from the earth strata below the layer known as the “organic layer.” Most societies in the past learned how to modify their local natural soil characteristics and mixing earths.

The soil utilized to manufacture adobes requires the plasticity of clay that gives consistency

to the mix for correct modeling. Therefore, the production starts with the dampening of the soil at a large scale for the correct breakdown of all clods of earth.

High moisture content in the mud and plasticity in its clays produce the risk of shrinkage, deformation, or cracking during drying. These alterations can cause problems in the transfer of loads and, above all, may allow infiltration of parasitic flora or fauna. Furthermore, the presence of fractures allows moisture penetration, the main cause of deterioration.

For this reason, most of the ancestral traditions in the adobe production consider the incorporation of added material that prevent shrinkage of mud mixture during the drying process, and improve structural tolerance and diminish vulnerability to moisture. These components are generically known as “stabilizers” and are greatly diverse, which would logically depend on available natural resources in each site.

Among the many stabilizers commonly used are cactus mucilage, bark extractions, soluble carbohydrates, lime, shredded straw, pine needles, horse or cow manure, as well as vegetal and animal fats or asphalt emulsions (Guerrero 2007, 188).

The wet and stabilized soil is mixed with available tools and techniques. Historically, the means used for mixing the mud have ranged from bare feet and hands to the use of horses and cattle hooves or garden tools. Traditionally, it was accustomed to allow the mix to sit for one or several days to improve the distribution of materials followed by molding the units.

The manufacturing process begins with the spreading of sand over the work site where a previously moistened wood mold or formwork is set. The mud mix is poured into the formwork and pushed into place with hands or feet, perfectly spreading it into the corners. Once the formwork is full, the top is screed flat and the adobe mold slowly lifted to prevent slumping along the edges.

The blocks are exposed to the air to allow homogeneous drying. When they reach the necessary strength for handling, they are turned on edge in order to properly dry for a period of 3 to 4 days, so that afterwards it is carefully stacked to allow proper ventilation between them. Drying time is fundamental to guarantee the proper

strength of all its constructive units. If an adobe is not completely dry, it is possible that the building can suffer deformations, weakening the structure as a whole.

Even though some texts mention that it “requires around three weeks” for an adobe to obtain its adequate strength (Prieto 1987, 80), Vitruvius (1914, 42–3) prescribed 2,000 years ago that adobes “should be made in spring or autumn, so that they may dry uniformly. [...] Bricks will be most serviceable if made two years before using; for they cannot dry thoroughly in less time. [...] This is so true that at Utica in constructing walls they use brick only if it is dry and made five years previously, and approved as such by the authority of a magistrate.”

The most common wall facing in one or two-story buildings is usually made with the width of the adobes oriented along the coursing of the wall. However, the facing varies considerably according to the proportions of the adobes, the wall height, the roof loads, as well as the regional seismic conditions.

The care for its course lapping is fundamental when comparatively describing a more fragile masonry system needing an adequate distribution of loads. Likewise, special attention should take place at corners and transverse wall connections, which are most vulnerable in buildings. The mortar has always been executed with a mix similar to the adobes and prior process of repose, to allow a proper moistening of its clay.

The adobe construction as we presently know it has evolved over millennia and has manifested throughout developed, organized, and diverse territories around the world. Adobe walls were used in buildings at Chan Chan in Perú, Djenné in Mali, and Bam in Iran. However, adobes were used to elevate mounds and fortresses, even to construct massive plinths. In these cases, it is typical for visitors to archaeological sites to not recognize its presence since the structures were veneered with stone or plastered for protection (Cornerstones Community Partnerships 2006).

Due to the vulnerability of adobe to moisture, these building systems normally require constructing over foundations—mainly stone footing—the implementation of roof overhangs

to prevent the impact of rain, and especially the application of plasters.

This adobe building system facilitated the development of numerous earth plaster types that were often enriched with moisture protective materials and paint. These plaster applications were used to implement high and low reliefs with a variety of designs that added to the rich value of this architecture.

Adobe was used to build arches, vaults, and domes. These architectural elements were common in areas with a limited amount of wood and lower levels of precipitation.

Adobe is one of the most common construction systems in the world, but has received little attention by investigators, preservationists, and professional contractors. Sometimes inhabitants of adobe buildings consider them unsanitary, unsafe, and associated with poverty because they ignore their historical and ecological values.

This is why the implementation of studies to examine the value and limits of adobe as a building system is fundamental to seek its preservation, and improvement, and to integrate present and future sustainable design.

This process opens various routes for the development of scientific research and practical work. These studies may include the physical analysis of old adobes, the chemical determination of stabilizing substances, crystallography, petrography, granulometry, chromatography, X-ray diffraction analysis, scanning electron microscopy (SEM), comparison of deterioration processes, evaluation of conservation alternatives used in different sites, typological documentation of building systems, among many others.

It is essential to rescue, value, and reuse this traditional architecture knowledge in order to apply it to new building design. However, this acquisition of knowledge might not be restricted to form or material composition, but requires the understanding of its architecture as a system (Guerrero 2007).

Additionally, it is necessary to identify and preserve the intangible heritage that constitutes the traditional knowledge seen today. It is essential to protect the materiality of historic adobe buildings in order to preserve their link with society (Guerrero and Uviña 2004).

Finally, it is crucial to disseminate adobe building knowledge among inhabitants, students,

architects, engineers, and government agencies. Furthermore, it is important to investigate the economic and ecological qualities of adobe architecture, thus allowing for the continuation of heritage architecture along with modern sustainable design.

SEE ALSO: Chromatography and Archaeological Materials Analysis; Conservation of Earthen Building Materials; Deterioration of Earthen Building Materials; Electron Microscopy in Conservation; Soil Chemistry in Archaeology; X-Ray Radiography and Material Analysis

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Ancient Mortars and Plasters

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Ancient mortars are mixtures made of inorganic binders, aggregates, water, and sometimes organic or inorganic additives that gave the mixture the desired workability and enabled the mortar to set and harden.

Ancient plasters are wall, roof, or floor coverings made up of one or more layers of mortar applied in a single construction phase.

Mortars can be divided into two macrotypologies: aerial mortars and hydraulic mortars. Aerial mortars set and harden in aerial conditions, while hydraulic mortars set and harden even when they are totally or partially immersed in water.

The raw materials used for making the inorganic binders of ancient mortars are carbonate rocks (limestone, marly limestone, dolomite, travertine), evaporite (gypsum), and metamorphic rocks (marble). Various types of mortars can be produced by mixing calcined raw materials with aggregates and water—for example aerial and hydraulic lime mortars, magnesium lime mortars, and gypsum mortars (both with aerial features).

The birth of pyrotechnology has greatly contributed to the diffusion and improvement of the production technology of mortars and plasters. It is probable that gypsum-based mortars go back further than lime-based mortars, because they can be produced at much lower temperatures (Elsen, van Balen, and Mertens 2012).

Evidence of the use of lime dates back to 11,000 BC and comes from the cave of Hayonim in Northern Israel (Vidale 2007; Artioli 2010). The most ancient mortar known to us today is probably the mortar that was used for making the floors in Yaftah (Southern Galilee) around 7000 BC (Bensted 1997; Pecchioni, Fratini, and Cantisani 2008). In the seventh and in the eighth millennium BC the production of lime and

gypsum plaster was quite complex, as evidenced by the building statuary and manufacture of containers in the Ancient Near East (Vidale 2007; Artioli 2010).

Many mortars that have been preserved until today have hydraulic properties. The hydraulicity of the binder can be due to the use, in the lime production process (calcination of the raw materials), of impure limestones with high content of silicon, aluminum, and iron (marls or marly limestones). In this way it is possible to obtain natural hydraulic lime.

Another way to obtain artificial hydraulic lime from aerial lime is by adding natural and artificial pozzolanic materials to the mixture. Natural pozzolanic materials are generally made of highly alkaline volcanic materials. The adjective “pozzolanic” came from “pozzolan,” a highly alkaline volcanic ash that the Romans used extensively between 300 BC and AD 200. The pozzolan (Figure 1a) was quarried from the Campi Flegrei area to the northwest of Naples, where the city of Pozzuoli is located (Artioli 2010). The most widely used artificial pozzolanic material in ancient times was crushed pottery mixed with brick fragments (*cocciopesto*), which was sometimes finely powdered (Figure 1b). Natural and artificial pozzolanic materials react with slaked lime, thus making the mixtures hydraulic and causing the formation of low crystallinity C-S-H phases (calcium–silicate–hydrate). Pozzolan was used for the construction of Minoan tanks in 1300 BC, as documented in the literature, while the Phoenicians used *cocciopesto* in the tenth century BC for coating tanks (Amoroso 2002).

Most often crushed pottery mixed with lime was used for the realization of hydraulic constructions like baths, tanks, and aqueducts. However, there are cases where crushed pottery and brick fragments were used to prepare mortars for structures that did not contain water, such as Roman floors and sidewalks (e.g., at Pompei). Crushed pottery and bricks were used also in joint mortars of ancient buildings; the joint mortars of Hagia Sophia in Istanbul, one of the most important buildings of antiquity, are an important example.

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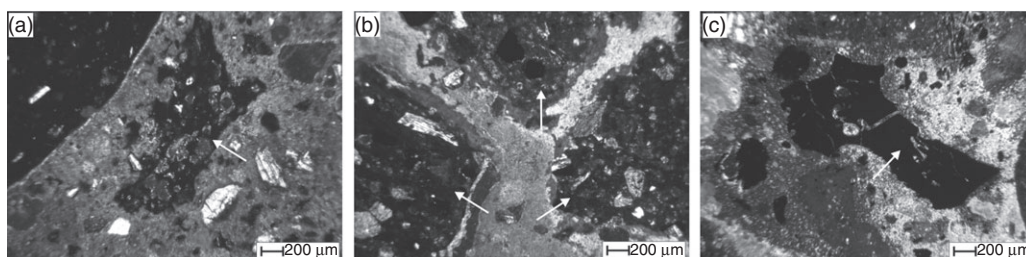


Figure 1 Microphoto of various types of pozzolanic materials under crossed polars: (a) Pozzolan fragment in the mortar from Casa di Pansa at the archaeological site of Pompei; (b) *cocciopesto* in the mortar from Casa di Pansa at the archaeological site of Pompei; (c) metallurgic slag in the mortar from the S. Niccolò archaeological site in Montieri, Tuscany. The sample was obtained from the Medieval Archaeology Group at Siena University, from a project directed by Giovanna Bianchi.

The crushed brick and lime of Hagia Sophia was classified as an advanced cement-based composite, which allowed the structure to survive numerous earthquakes (Moropoulou et al. 2006).

The Romans used natural pozzolan extensively in the production of joint mortars in different parts of the empire; but they were not alone. Populations in Mesoamerica, for instance the Mexicas, used natural pozzolanic materials in the production of lime plaster. The lime plasters from Templo Mayor (the Great Temple), the main pyramid of Tenochtitlan in Mexico, are a case in point. In Mexico the volcanic pozzolanic fragments are known as *tezontle* and show a variable color, which can go from dark grey to red.

In addition to pozzolan and *cocciopesto*, other natural and artificial materials were used in ancient times for producing hydraulic mortars: diatomaceous earth, metallurgic slags (see Figure 1c), kaolin, and opal-A. The medieval hydraulic mortars found in the tower of Pisa in Tuscany were produced by mixing slaked lime with diatomaceous earth, which was probably quarried at Mt. Amiata (Franzini et al. 2000), approximately 180 kilometers to the south of Pisa.

Various types of organic raw material mixed with lime were used to produce mortars and plasters in antiquity. The practice of adding charcoal to lime is described in Pliny's *Natural History* (Book 36, ch. 63). Vegetal charcoal (Figure 2a) was used as an aggregate in the plasters of the large early Christian baptismal font found during the excavations carried out at the Church of Son Peretò in Mallorca.

In Mesoamerica, evidence was found of the use organic materials such as mucilage of nopal,

a particular type of Mexican cactus, in the production of lime plasters. In ancient China, sticky rice and lime were mixed together to make mortars and plasters. In the archaeological site of Kyme in Turkey it was found that vegetable fibers (Figure 2b) were used for making lime plasters from the fifth to the seventh century AD. The scientific debate regarding the function of the organic substances that were added to the mortars and plasters in antiquity is still open.

Out of all ancient societies, the Romans were probably the most highly skilled in the production of mortars and plasters, and by reading Vitruvius' *De architectura* and Pliny's *Natural History* we can clearly see how much importance they accorded to the type of the raw materials used for making mortars and plasters and to their preparation.

Pliny stated that lime putty should be left to age for at least three years in order to make a good lime binder. The slow aging of lime putty reduces the size of the portlandite crystals ($\text{Ca}(\text{OH})_2$), thus improving the characteristics of the mortars and plasters.

Vitruvius, in Book 7 of his treatise on architecture, speaks of seven layers of mortar in the preparation of plaster. At the house of Longus on the archaeological site of Pompei, there is an plaster, approximately 5 cm thick, made of six layers of mortar; despite being almost 2,000 years old, this plaster is very well preserved and solidly attached to the wall. The first five layers are made of a mixture of lime and pozzolan, with the grain size decreasing from inside to outside; the last layer is made of a mixture of lime and finely crushed marble powder.

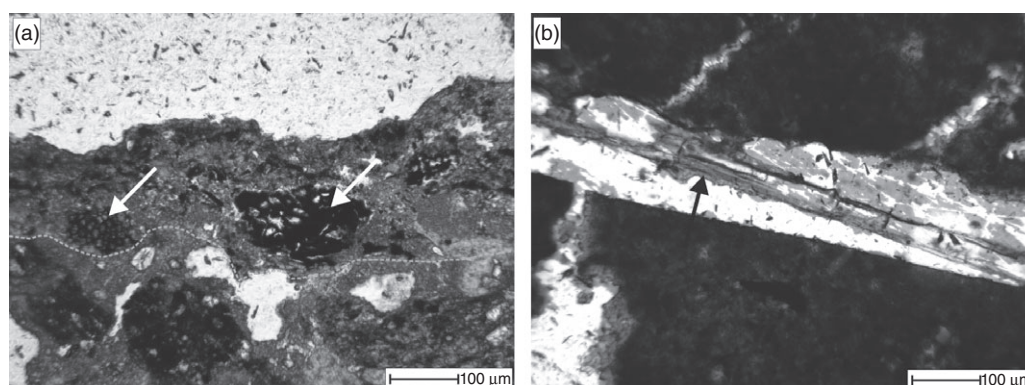


Figure 2 (a) Microphoto under parallel polars of charcoal used as aggregate in the lime plaster from the large early Christian baptismal basin in Son Peretò (Mallorca, Spain). The sample was obtained from the Equip de Recerca Arqueològica i Arqueomètrica de la Universitat de Barcelona (ERAAUB), directed by Miguel Àngel Cau Ontiveros; (b) Microphoto under parallel polars of a vegetable fiber in lime plaster of the fifth–seventh centuries AD from the archaeological site of Kyme in Turkey; the sample was obtained from Antonio Lamarca, the director of the archaeological mission in Kyme.

If the Romans often mixed lime with other raw materials, to various proportions, to make all the layers of the plaster, other societies prepared the first layer with different raw materials, as we can see by observing lime plasters from the ancient Mexican city of Teotihuacan. In Teotihuacan, the floor of the main courtyard at Teopancazco was made of two superimposed layers of plaster (Barba et al. 2009): the inner preparatory layer was made of beaten earth mixed with crushed volcanic rocks without lime; this layer was known locally as *firme*. The external layer, which was approximately 2–3 mm thick, was made by mixing lime with volcanic glass shards and was known locally as *enlucido*.

Mortars and plasters are considered to be artificial stone materials similar to sandstone, which is a sedimentary rock. The mortars preserve the technological imprint of the workers who produced them. A detailed compositional study of the mortars can provide valuable insight into the technological know-how of a certain historical period. It is likely that mortars with similar compositional characteristics belong to the same construction phase. For this reason, mortars can be used to solve issues such as the individuation of the constructive phases of an ancient building. The most suitable mortars for establishing the construction phases of an ancient building are

“joint mortars,” which are wall mortars that link two bricks or two building blocks.

Archaeometric studies on mortars, focused at the recognition of constructive phases, depend on the quality of the sampling in situ. The samples should be selected on the basis of preexisting archaeological hypotheses. The number of samples must be statistically representative of the compositional variability of the mortars: this is because the mortars are heterogeneous materials and the size of the clasts that form the aggregate can range greatly.

The best approach for understanding the secrets of the ancient mortars and plasters is the multianalytical approach. The analytical techniques most widely used for studying the composition of mortars and plasters are the same techniques that are generally used for the compositional characterization of rocks: polarized light microscopy (PLM), X-ray fluorescence (XRF), X-ray powder diffraction (XRPD), and scanning electron microscopy with X-ray microanalysis (SEM–EDS). Specific analytical methodologies can be used together with the above-mentioned techniques for carrying out in-depth studies on the mineralogical composition of the aggregate and the binder and for determining the provenance of the raw materials used for their production: laser ablation inductively coupled with plasma mass spectrometry (LA–ICP–MS),

micro-Raman spectroscopy (MRS), transmission electron microscopy (TEM), Fourier transform infrared spectroscopy (FTIR), differential scanning calorimetry (DSC), thermogravimetric analysis (TGA) and image analysis performed on thin section.

However, PLM is deemed superior to other techniques and is essential for studying the petrographic and micromorphological characteristics of mortars; moreover, PLM is required to program, optimize, and better interpret all of the analyses carried out on the samples. Two mortars may have the same chemical and mineralogical composition and a different petrographic composition at the same time; only by performing PLM on thin sections can we avoid making this type of mistake.

A good analytical step-by-step approach for studying ancient mortars and plasters consists of:

1. macroscopic observation of the mortars during and after the sampling;
2. a preliminary study of the samples in thin sections with transmitted PLM and XRPD analysis of the bulk sample;
3. recognition of the geochemical groups using the cluster analysis on XRF data; and
4. the validation of the geochemical groups with PLM on thin sections and the recognition of the various construction phases.

Subsequently the binder can be studied by:

1. identifying the lime lumps in thin sections with PLM;
2. analyzing the lime lumps and the binder through SEM-EDS analysis and LA-ICP-MS;
3. studying the C-S-H phases of the binder with the TEM analysis.

The study of the binder in the ancient mortars, linked to the evaluation of their degree of hydraulicity, is a complex problem. The complexity arises from the difficulty to detect and quantify the hydraulic compounds in the binder fraction. If their crystallinity is high, it is possible to use X-ray powder diffraction (XRPD) to detect the C-S-H phases; on the other hand, it is possible to use thermogravimetric analysis (TGA) to make a distinction between hygroscopic water,

water from hydrated salts, and the loss of the water bound to hydraulic compounds (Elsen, van Balen, and Mertens 2012). Another promising method for obtaining information about the distribution of the hydraulic compounds in the binder fraction is micro-FTIR imaging, coupled with attenuated total reflectance (Diekamp et al. 2012). The method is based on the study of the reaction rims around the pozzolanic materials; in particular, it allows identification of the group of bands between 900 and $1,120\text{ cm}^{-1}$, which is assigned to Si-O stretching vibrations indicating C-S-H phases. The hydraulicity of the binder of mortars and plasters can also be highlighted by studying the Si/Ca ratios in the reaction rim through scanning electron microscopy with X-ray microanalysis (SEM-EDS).

In recent years, various techniques such as optically stimulated luminescence (OSL) and radiocarbon (^{14}C) have been used for the dating of ancient mortars. Although satisfying results have been obtained through these techniques, they have not yet been fully consolidated for dating mortars and plasters. Not all ancient mortars and plasters can be dated by means of radiocarbon (^{14}C) and OSL; the correct application of these techniques depends on mineralogical composition and on the extent of decay. Moreover, in order to apply the radiocarbon (^{14}C) to the binder and lime lumps contained in the mortars, it is essential to study the mortar with an optical microscope under transmitted polarized light and Fourier transform infrared spectroscopy (FTIR), to determine the various types of calcium carbonate and to separate them from the calcite formed during the carbonation process of the lime; in fact, in addition to lumps and binders, mortars may contain different types of calcium carbonate: secondary calcite crystals that form within porosity; fragments of carbonate rocks contained in the sands used as aggregate; or even fragments of mortar older than the one to be dated, deriving from secondary raw materials that are reused as aggregates in new mixtures.

It is seldom possible to identify and extract traces of charcoal from ancient mortars and plaster, which remained as residues of the combustible material used during the calcination of the limestones. With a sufficient amount of

charcoal it is possible to date the mortars using the radiocarbon (^{14}C) method.

In most cases mortars and plasters are made with raw materials that can be found in close proximity to the architectural structure to which they belong. However, this is not always the case, and the provenance studies carried out on raw materials used for producing mortars can sometimes give very interesting results. The raw materials used for preparing mortars are aggregates and carbonate rocks used for producing lime. In recent years, good results have been obtained with laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), which is used for establishing the provenance of ancient mortars and plasters. This technique has been successfully applied in determining the provenance of the aggregate and limestones used for making the plasters that covered the floor of the main courtyard at Teopancazco (Barba et al. 2009), at the archaeological site of Teotihuacan. The lime lumps that form during the slaking of the lime preserved the chemical composition of limestones with which they were produced. LA-ICP-MS analyses were performed simultaneously on the lime lumps and on the probable quarries of the limestone in order to determine the major elements and the trace elements. The results showed that Tula (85 km west of Teotihuacan) was the only possible source of the limestone used for making the Teopancazco courtyard plaster. The same approach was applied to determine the provenance of the volcanic aggregate (glass shards) found in the plaster of the Teopancazco courtyard and determined that the glass shards came from the Altotonga magmatic system, located 180 km east of Teotihuacan. These results showed that the place of provenance of the raw materials of the mortars and plasters was quite a long way from the archaeological area, thus enabling archaeologists to trace ancient trade routes.

Another very important aspect in the study of ancient mortars and plasters concerns the compatibility of the repair mortars used for restoring an ancient building. A repair mortar is generally considered to be fit for purpose when it is aesthetically, chemically, mineralogically, mechanically, and physically compatible with the substrate on which it is to be applied. At the end on the nineteenth century and throughout

most of the twentieth, Portland cement was widely used for restoring ancient monuments, yet many compatibility issues have arisen between ancient lime mortars and Portland cement over the years. The best way of making mortars that are compatible with ancient ones would be to find all of the original raw materials used in the mixture, which could then be used to produce new mortar. It is therefore essential to carry out in-depth analyses on the ancient mortars and plasters used for construction before restoration.

SEE ALSO: Cluster Analysis; Compositional Data Analysis; Dating and Optically Stimulated Luminescence; Dating in Archaeology; Diffraction; ICP-MS and Material Analysis; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Multivariate Analysis; Optical Microscopy; Pyrotechnology of Cements; Raman Spectroscopy and Material Analysis; SEM-EDS and Material Analysis; TEM and Archaeological Materials; Volcanic Rock Sourcing; X-Ray Fluorescence Spectrometry (XRF); XRD and Materials Analysis

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Bones and Ivory

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Bone and ivory are the predominant materials of animal origin to survive within the archaeological environment. They are an organic source of information that can elucidate our understanding of past animal species, diets, diseases, aspects of domestication, trade, materials, and technologies, as well as the utilization of raw materials, but more importantly the relationship between animals and people of the past. Since bone and ivory are derived from animal skeletal remains, they form part of the natural cycle of decay as organic material, and are therefore unlikely to survive burial intact, in comparison to inorganic remains such as lithics (stone), metals, and ceramics. Usually, archaeological bone and ivory remains are amorphous, without discernible shape due to their fragile and fragmentary state. Specialist knowledge of modified or worked bone and ivory, in particular, is fairly limited, as research tends to approach each material differently, despite their similar chemical composition and signatures. Any research approach should, however, investigate archaeological bone and ivory based on an understanding and appreciation of their composition as raw material (Tiley-Nel and Antonites 2015).

Bone is a mineralized connective tissue that forms the skeletal support of vertebrate animals, whereas ivory is the unusually large projecting teeth or tusks of animals. Other protein-based organics include shell, horn, and antler, leather or hide, and hippopotamus and warthog ivory. Collectively, these are also referred to as osseous materials, which are the hard body parts of animals, including bone, antler, teeth, ivory, turtle shell, hooves, and horns (O'Conner 1987).

Animal bone is essentially the skeletal material (bony elements) or anatomical part of a mammal's internal skeleton. Bone is a mineralized connective tissue primarily comprised of two

main elements: organic matrix (collagen-protein) and inorganic mineral (hydroxyapatite). The mineral part of the bone is comprised mostly of calcium and phosphorus, with small amounts of fluorine, sodium, and magnesium. The main carbon-based portion of bone is composed of a protein called ossein. Bone has two major types of structures, namely the cancellous bone and the more compact or cortical bone. The light cancellous or spongy tissues are found within the interior of bones, and the heavier, denser, compact tissues are found on the outside, and in the long shafts of long bones. Compact bone, which makes up the shafts of limb bones (long bones), tends to have a laminated structure on their external surface. Since compact bone is usually tubular, it is frequently used for cylindrical artifacts such as handles and bone tools, which are cut from strips of compact bone. Despite its compact appearance, bone is remarkably porous on a very fine scale, which helps to hold the bone marrow or soft tissue that produces red blood cells. The porosity of bone is likewise due to the make-up of canals that store the nerves and blood vessels (O'Conner 1987; Cronyn 1990).

Ivory, as distinguished from bone, includes tusks and the large projecting teeth of animals. Although the term "ivory" is traditionally applied to the tusks of elephants (the order of Proboscideans), it includes teeth and tusks from mammoth, walrus, killer whale, sperm whale, narwhal, hippopotamus, and several pig species such as warthog, boar, and bush pig. It is relatively easy to distinguish among the various animal ivories by the characteristic geometric growth and the layering of organic and inorganic matter according to well-defined patterns (Espinoza and Mann 1992, 10). Ivory is primarily composed of another form of bone called dentine, which in turn is coated with enamel and cementum. The organic component makes up about 20 percent of living dentine, with about 70 percent mineral component and the rest water. The dentine contains a microscopic structure called dentinal tubules, which form long sheets referred to as micro laminae (Locke 2008). These laminate or lamella are sometimes called the "grain" of

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ivory and it is prone to extreme warping and delamination, a signature characteristic of ivory, because when buried it becomes brittle as the laminate or growth layers degrade over time (Tiley-Nel and Antonites 2015, 16–18).

Ivory is also one of the hardest organic materials, but because it has poor elastic properties, any area that is under pressure is subject to the formation of cracks or material loss. In transverse section, elephant ivory exhibits a unique pattern of intersecting lines, which form small diamond-shaped areas visible to the naked eye. This distinctive structure characterized by the intersecting lines is also known as the so-called Schreger pattern (Locke 2008). The intersections of Schreger lines form angles which appear in two forms: concave angles and convex angles. This chequered or cross-hatch pattern aids in positive identification of elephant ivory, as it can be seen by the unaided eye on transverse profiles or by discoloration of the surface (Tiley-Nel and Antonites 2015). The significance of the Schreger pattern has important taxonomic implications, as this exclusive feature is highly important in the identity of true ivory and is singularly characteristic of most proboscidean ivory (Espinoza and Mann 1992).

Both bone and ivory have complex compositions comprising two components: the inorganic mineral (hydroxyapatite) and the organic matrix (collagen-protein). It is the inorganic component that provides strength and rigidity and the organic component that provides the capacity for growth and repair. The inorganic component consists of mineral hydroxyapatite (an insoluble salt of calcium and phosphorus or calcium phosphate) and the organic component consists of mainly collagen and small quantities of lipids. Both the inorganic and organic component of bone and ivory also contain water, some of which is lost over time, thus leading to hardening. These elements have very different functions and properties, which, in combination, allow bone and ivory to be hard and flexible, so as a result excavated bone and ivory are sometimes visually indistinguishable and are therefore used as an ideal raw material for the manufacture of artifacts (Py-Daniel 2014).

Worked bone and ivory have the potential to inform archaeological interpretations about the production of raw materials into artifacts. Therefore, an important constituent of modified

bone and ivory into artifacts is the proper identification of the raw materials chosen to make them. The surface structure and morphology of modified animal bone and ivory can lead to greater accuracy in identification (Espinoza and Mann 1992). Observations of shape, color, hardness, texture, deterioration, signs of damage, and other physical qualities relate to the nature of the raw material and to techniques of manufacture. Furthermore, such information is critical to determine the specialized conservation needs of bone and ivory and to make informed choices about appropriate analytical techniques because bone and ivory are often suitable samples for a number of archaeometric methods such as radiocarbon dating, trace use-wear analysis, isotopic analysis, and organic residue analysis (see ORGANIC RESIDUE ANALYSIS). Bioarchaeology (see BIOARCHAEOLOGY) specifically investigates the survival of biomolecules on animal tissues, such as protein focusing on degraded collagen and albumin. Furthermore, it is well known that proteins survive longer than DNA, and, in recent studies, scientific techniques such as the analysis of ancient DNA (aDNA) and proteomics or the study of proteins aid archaeological knowledge of the longevity of protein survival in ancient bone.

Proper identification and investigation of the raw material can reveal potential evidence, such as the nature of the material, and its physical properties, structure, and composition. However, many changes similarly occur to archaeological bone and ivory, especially when exposed to adverse environmental conditions. These variations can alter the physical structure and chemical composition, and lead to further changes such as damage and deterioration. The processes that change the nature of bone and ivory during burial and how these processes are determined environmentally are often referred to as diagenesis (see DIAGENESIS OF BONE). Due to their inherent fragile nature, there are numerous types of pre-burial, burial, and post-excavation changes to archaeological bone and ivory in particular. It is therefore important to distinguish between chemical and structural damage resulting in surface modifications on bone and ivory, which is fundamentally important to zooarchaeology (see ZOOARCHAEOLOGY) as well as to the study of the conservation of organic materials. Preservation of bone and ivory varies considerably, because

they are made up of both organic and inorganic constituents, which are preserved at opposing pH; that is, the measure of alkalinity or acidity of the surrounding environment essentially determines the extent of preservation (Cronyn 1990).

Buried bone and ivory are modified by and weathered from physical and chemical processes, the result of which can be cracking, splitting, exfoliation, disintegration, delamination, abrasion, decomposition, or degradation. Ivory is particularly reactive to its environment and is very sensitive to any changes in relative humidity, moisture, and temperature. This causes further delamination and color changes, such as lightening when exposed to light or darkening as a “patina” which may also be evident as a result of the natural aging process of ivory’s organic constituents. The slightest temperature variance in the environment and exposure to moisture will cause damage in both ivory and bone (Cronyn 1990). This is because bone and ivory are both anisotropic and hygroscopic; that is, they have different physical properties in each direction, meaning that moisture changes can exert stress or tension on their physical structure, resulting in damage and deterioration (Lafontaine and Wood 1982).

Although bone and ivory are complex in structure and morphology, but have similar chemical signature compositions, being composed of both organic and inorganic components, they are preserved at opposing pH (potential of hydrogen). Therefore, pH is essentially one of the largest influences on the loss of these organic materials. The inorganic hydroxyapatite deteriorates in acidic environments, while the collagen (organic) deteriorates in alkaline environments. In acidic conditions, the inorganic components dissolve, leaving ivory to shrink when it dries out, causing warping, delamination, and material loss, whereas acidic conditions will result in the leaching of bone minerals, causing bone to lose strength and rigidity as it becomes friable (Cronyn 1990, 277).

By means of archaeological investigation, proper museum conservation, curation, and collections management practices enable studies of bone and ivory as raw osseous materials. Such practices allow for closer examination of the traces left by animals and human and natural modifications which can elucidate valuable research information about the manufacture, use, and discarding of modified bone and ivory.

Also an in-depth understanding of the structure, composition, and constituents of bone and ivory can be fundamental to the comprehension of excavated organics, as well as understanding how and why they survive the archaeological record.

SEE ALSO: Conservation of Bone, Horn, and Ivory

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Cements, Mortars, Binders

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Overview

Cements, mortars, and binders are materials with adhesive and cohesive properties primarily used for construction purposes. They form an important class of building materials and have been employed to create, protect, or decorate buildings and engineering works for at least 10,000 years. Over the last decades, as interest in ancient building materials and practices has grown, a substantial number of investigations have been devoted to the analysis of samples taken from old masonry structures, finishing coatings, and ornamental elements. Typically, the materials sampled have been analyzed for (1) determining their composition and properties; (2) deriving information about their production and its organization; (3) assessing their age; or (4) understanding the causes of their degradation and evaluating repair and conservation strategies. A variety of analytical techniques have been used, and several standard protocols have been proposed to guide mortar characterization.

Mortar terminology

Ancient mortars have attracted the attention of many specialists from different fields, not only from archaeology, history, and conservation science, but also from architecture, civil engineering, and materials science. Many terms have been used to describe them; and the lack of a common vocabulary across disciplines has led to inconsistency and confusion in terminology. Different materials have been designated by the same

term and different terms have been applied to the same material. The terms “cement,” “mortar,” and “binder” are no exception in this regard and have been adopted as both generic and specific names for various materials. The terminology proposed here follows the most common usage and each of these three terms is assigned to a specific material.

Mortars may be defined as composite materials obtained by adding water to a mixture made up of two basic components, a binder and a filler. The binder is the substance that gives consistency and adhesiveness to the mortar. It forms a continuous matrix and plays an essential role in the setting process. While it is not impossible to use a binding substance alone, in practice it is often necessary to add a filler, that is, a material that gives it bulk, strength, and stiffness. Usually this material consists of finely divided mineral matter, or of aggregates. Additional components eventually incorporated into the mix to further enhance its performance or to achieve special properties are usually regarded as additives. Water is used to make the mixture plastic and workable long enough for it to be properly placed and shaped. Once in place, the paste progressively hardens into a solid and relatively permanent material as the binder sets.

It is to be noted that the terms “binder” and “cement” are frequently used interchangeably. However, in its more restricted sense, “cement” only refers to a specific type of binder, produced with modern equipment and technologies. Moreover, it should also be specified that mortar and concrete are similar in composition. Concrete is also composed of water, a binder, and a filler. It may, however, be regarded as a distinct material, since it contains both fine and coarse aggregates. The use of sand, gravel, or crushed stone as aggregates significantly affects the physical and mechanical properties of the final product. Unlike mortar, concrete has no binding force, but can be used alone and is strong enough to bear heavy loads.

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Applications

Many different kinds of buildings constructed with mortar still survive in different parts of the world. They attest not only to the widespread use of mortar, from prehistory up to the present day, but also to the great variety of mortar types. Archaeological and historical evidence suggests that the selection of a particular mortar was determined by several factors, including the availability and cost of raw materials, local building practices, and mortar applications. As it is extremely versatile and easy to produce in various forms, mortar has fulfilled a wide range of functions. Briefly, it may have served as (1) a bonding material (for bedding, jointing, and pointing stones and bricks, or for infilling masonry structures); (2) a finishing material (for internal plastering, external rendering, flooring, waterproofing, and sealing); or (3) a decorative material (for casting, molding, modeling, and fixing or supporting architectural ornaments).

Materials and production methods

Before the industrial revolution, mortars were prepared using raw materials essentially derived from locally available resources. The most common binders were mud, gypsum, and lime, or combinations of these substances. Organic binders such as bitumen, natural oils, waxes, and resins were also used, but to a lesser extent. Over the course of the eighteenth and nineteenth centuries, with the emergence of cement-based products, the use of these traditional binders declined. Natural, then artificial cements became the predominant types of binder in use.

Mud-based mortars

The most basic binder used to produce mortar is mud, or earthen material. Earth is available almost everywhere and can easily be made into a malleable paste through the addition of water. Given the variability of soil types from place to place, the properties of the material obtained can differ widely. Generally, however, the most suitable soils are characterized by a homogeneous particle size distribution and by a moderate

proportion of clay minerals. The clay content is especially important, since it determines the cohesive strength and the plastic behavior of wetted earth, as well as its drying shrinkage rate. If the proportion of clay minerals is too low, the mud will lack binding force; if it is too high, the mud will tend to crack on drying. Unlike gypsum and lime binders, mud simply sets and solidifies by desiccation, without undergoing chemical change. Although some soils may produce relatively good mortars without further modification, mud-based mixes are traditionally improved by adding mineral aggregates and fibrous matter. The addition of copious quantities of chopped straw or other natural fibers helps increase strength, control shrinkage, and reduce cracking. Mud may also be combined with lime or other additives in order to prevent the formation of cracks and provide better water resistance and durability.

The resilience of mud and the tendency of earthen materials to promptly soften and crumble if unmaintained or exposed to natural elements partly explain why ancient mud mortars have left rather scant and poorly recognizable archaeological evidence by comparison to other bonding and plastering materials (see DETERIORATION OF EARTHEN BUILDING MATERIALS). Pieces of accidentally burned mortars and plasters or exceptionally well-preserved remains show, nevertheless, that this type of mortar has been extensively used, at least since Neolithic times and in nearly all preindustrial societies. Moreover, although its popularity has progressively decreased in the recent past, it still continues to be a material of choice in various regions of the world.

Gypsum- and lime-based mortars

Gypsum and lime are among the earliest examples of artificial materials whose production depends on chemical modification by fire. The discovery that, once burned and ground, certain rocks can be mixed with water to produce a paste that may be used in the same way as mud seems to be intimately connected with the advent of pyrotechnology, some 10,000 years ago. The process by which these rocks are converted into binding materials is, however, more complex than preparing the mud and involves various chemical reactions. As it starts with the disintegration of the

raw material and ends with its reintegration, this multistep process is often referred to as a “cycle.”

The gypsum cycle can be divided into two major steps: the calcination and the hydration of gypsum minerals. In nature, such minerals are typically found in gypsum rocks, in the form of calcium sulfate dihydrate ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$). When subjected to fire, gypsum loses its combined water. The dissociation process starts at approximately 70°C and, at $100\text{--}200^\circ\text{C}$, gypsum turns into hemihydrate ($\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O}$: bassanite). Further heating removes all the water and leaves anhydrous calcium sulfate (CaSO_4 : anhydrite). It should be mentioned that naturally occurring anhydrite rock can also be used for gypsum production without the need to calcine it. The dehydration of calcium sulfate, either partial or total, is simply reversed through the addition of water. When powdered burnt gypsum is mixed with water to form a soft paste or a slurry, hemihydrate and anhydrous sulfate recombine with water molecules, recrystallize, and revert to a dihydrate state. Consequently, the starting and the end products are chemically similar. Powdered bassanite, also known as “plaster of Paris,” quickly reacts with water and is converted into a mass of tiny interlocking crystals that allow the mortar to cohere and set into a rigid, new stone-like material. Anhydrite is less reactive. It takes much longer to hydrate, and thus to set.

By comparison to lime-based mortars, gypsum mortars have various advantages. First, since they require relatively low temperatures for their processing, they offer an interesting alternative in regions with limited sources of fuel. Second, their setting time can be easily controlled through the addition of modifiers that act as retarders or accelerators, such as organic gum, glue, and starch, or finely ground raw gypsum, and water-soluble salts.

Finally, gypsum mortars dry and harden with negligible shrinkage. They can therefore be used with a minimal amount of aggregates. Slight water solubility and low weather resistance in humid environments are considered their main drawbacks, but these problems have often been bypassed by adding lime or waterproofing agents.

The starting material for making lime is limestone or some other material composed predominantly of carbonate, such as marble, shells, or coral. The main constituent of limestone

is calcium carbonate (CaCO_3 : calcite), but limestone is rarely pure and frequently contains other minerals that can also be subject to physical and chemical changes during the lime-cycle process. When magnesium carbonate (MgCO_3 : magnesite and $\text{MgCa}(\text{CO}_3)_2$: dolomite) represents a significant component, as for example in dolomitic limestone, the resulting product is known as a magnesian or dolomitic lime. The presence of noncarbonate minerals such as clays or other siliceous and aluminous constituents may influence the setting mechanism and, according to their importance, two categories of lime can be distinguished: air lime and hydraulic lime.

In order to be converted into lime, carbonate materials first have to go through two main stages: thermal treatment (calcination) and slaking (hydration). The heating of carbonate minerals at appropriate temperatures causes their decomposition and the removal of carbon dioxide. Calcium carbonate begins to lose carbon dioxide at 700°C , but its full decomposition usually takes place around 900°C . Magnesium carbonate dissociates between 510°C and 750°C . The next stage, known as slaking, consists of mixing the burnt residue with water. Calcium oxide (CaO : quicklime) reacts exothermically with water and turns into calcium hydroxide ($\text{Ca}(\text{OH})_2$: portlandite). Magnesium oxide (MgO : periclase) is less reactive and slowly reverts to magnesium hydroxide ($\text{Mg}(\text{OH})_2$: brucite). Unlike gypsum, lime requires a third stage in order to set, and the nature of this final stage differs according to the purity of the parent material.

Limestone and materials high in carbonate content produce air lime or nonhydraulic lime. Lime made from limestone containing clays and other silicates and aluminates in significant proportions is known as hydraulic lime. Nonhydraulic lime sets by drying and reacting with atmospheric carbon dioxide, to form calcium and magnesium carbonate again. This process, called “carbonation,” is extremely slow, and uncarbonated lime lumps have been observed in mortars several centuries old. Hydraulic property, or hydraulicity, derives from the reaction between calcium oxide and some of the noncarbonate constituents, especially silica and alumina. Intense heat causes these components to react with lime and induces the formation of calcium

silicates and aluminates. When these come into contact with water, they turn into calcium silicate and aluminate hydrates (C-S-H and C-A-H), that is, into low-solubility compounds that confer hydraulicity or the property to set in wet conditions, even under water.

There is strong evidence that, relatively early in the history of lime technology, artificial hydraulic limes were produced by mixing ordinary lime with certain siliceous materials in a finely divided form. In the presence of water, the silica–alumina components present in these materials react in the same way as those naturally contained in some limestones. Such materials, which have been given the name “pozzolan,” may be natural or artificial. Natural pozzolans mainly consist of materials of volcanic origin such as ash, tuff, and other pyroclastic rocks. Other forms include opaline cherts, shales, and some diatomaceous earths.

Historically, artificial pozzolans were obtained through the pulverization of fired clay-based materials such as bricks, tiles, and pottery. Nowadays common alternatives include specifically manufactured clay products (metakaolin) and industrial wastes (fly ash, silica fume, rice husk ash, and so on).

Initially the term “pozzolan” was used to describe the volcanic materials (*pozzolana*) mined in the vicinity of Pozzuoli near Naples (Italy) and employed since Roman times in the manufacture of hydraulic binders. It is generally believed that the practice of adding natural and artificial pozzolans to lime appeared during the first millennium BCE and was diffused through the Greeks and the Etruscans to the Romans. Recent discoveries and archaeological records from other regions rather suggest that this practice had antecedents and parallels not only in the Neolithic Levant and in the Bronze Age eastern Mediterranean region, but also in more distant areas such as pre-Hispanic Mesoamerica (Hauptmann and Yalcin 2000; Theodoridou, Ioannou, and Philokyprou 2013; Gillot 2014).

Like gypsum, lime offers various advantages over mud in terms of versatility, applicability, strength, and durability. Furthermore, compared with gypsum mortars, lime mortars better retain their integrity in damp environments. Hydraulic mortars are also useful for the construction of hydraulic works and immersed structures. From a technological perspective,

however, lime production is more expensive and energy-consuming, since the calcination of carbonate materials requires a substantial amount of fuel to maintain high temperatures for several hours or days. Prior to the advent of modern kilns fueled by oil and gas, lime was produced in various types of kilns, from the earliest open-air bonfires and pit ovens to traditional, built lime kilns. The load was not necessarily well separated from the fuel, and ash and charcoal inclusions regularly contaminated the lime. In addition, as firing temperatures and heat distribution were not easily controlled, lime was not always burned uniformly. Under- or overburned particles inclined to slake slowly or incompletely were frequent.

Quicklime was converted into lime by various dry and wet methods. Dry slaking was often achieved by mixing lime with a limited quantity of water or damp sand. Nonhydraulic lime was also commonly slaked to a putty, then set aside for long periods of time in order to ensure that all particles were fully slaked and to allow the product to mature or “age.” When required for use, lime powder or putty was blended with aggregates and, if necessary, with additional water. Well-graded natural sand and pulverized stone were the most common aggregates. Other aggregates included chunks of chalk, shells, and various recycled materials like fragments of brick, pottery, and old mortar. Considerable variation occurred in the binder–aggregate ratio but, ideally, the aggregate was mixed with just enough binder to fill the voids between its particles. Modern specifications for lime mortars usually prescribe one part of lime for three parts of aggregate. Old lime mortars rather show a ratio that varies between 1:1 and 1:4. Finishing plasters and renders were typically prepared with a higher proportion of lime.

Additives were normally added in small quantities. A wide variety of additives have been used; they include various dairy products and substances of animal or vegetal origin (ash, fibers, dung, blood, oil, glue, resin, sugar, beeswax, beer, milk, rice, etc.). Inorganic and organic colorants were also sometimes added to surface coatings composed of water-based solutions of lime (limewash).

Cement-based mortars

At the dawn of the industrial revolution, the search for optimal hydraulic binders led to significant developments in lime-mortar technology and opened the way to the manufacture of a new class of materials called “cements,” in an allusion to the ancient Roman concrete (*opus caementicium*). Cements are highly hydraulic binders, made by calcining either natural calcareous materials rich in clay minerals (natural cement) or artificial mixtures of calcareous and argillaceous materials (artificial cement). During the hundred years between 1750 and 1850, various attempts were made to produce such binders. Different cementing products appeared on the industrial market, the most famous being those of James Parker and Joseph Aspdin. Natural cements, such as Parker’s Roman cement, patented in 1796, appeared first and predominated until the late nineteenth century. Later, however, they fell into disuse, as artificial Portland cement, first patented by Aspdin in 1824, became the norm.

The technological improvements and advances associated with the manufacture of Aspdin’s product provided the basis for the modern cement industry. Materials with high proportions of clay minerals were selected and calcining temperatures were increased, so that they approached the sintering point (around 1,450°C). At this temperature, carbonate and clay minerals fuse to form complex compounds such as dicalcium and tricalcium silicates (belite and alite). On cooling, the molten mass vitrifies and is converted into hard clinkers, which must be repulverized to generate a powder highly reactive with water. When water and cement are mixed together in the course of preparing a paste or a mortar, the hydration and setting processes start almost instantaneously.

Like hydraulic lime mortars, cement-based mortars retain their integrity and stability under either atmospheric or submerged conditions.

With their quick setting time, impervious character, and high compressive strength, cements were rapidly adopted, first for large industrial application and then in all forms of construction. During the last two centuries the demand for cementing products has increased, and constant efforts have been made to meet the requirements of modern building and engineering industries. This has resulted in the emergence not only of a variety of specialized cements, but also of a large number of new additives and chemical admixtures.

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Characterization of Ceramics

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Ceramics and archaeology

While this definition may vary between research disciplines and the timeframe under consideration, ceramics can be described as objects made out of clay that has in some way been processed. Clay is a naturally occurring geological deposit, usually formed from the weathering of rocks. It is made up of clay minerals mixed with a greater or lesser amount of other minerals. Common clay minerals encountered in the deposits used for archaeological ceramics include kaolinites, smectites, chlorites, and illites. Naturally occurring clay bodies often combine a wide range of different clays within these groups. Different clay types give slightly different properties to the ceramics that are made from them. “Clay” is used in this text as a term indicating a natural geological deposit made up mainly of clay minerals, often mixed with other minerals.

The simplest type of ceramic would be clay that has been shaped and dried, while more complicated ceramics would be fired in a kiln at temperatures that fuse the outer layer of the clay minerals in its body and give the object strength and resistance to moisture and heat. In arid climates, dried or baked clay bricks are still used in architecture as they have been for many thousands of years. However, such baked clay is vulnerable to damp, and rapidly turns back to clay when subjected to contact with water. From the Neolithic, clay was shaped and *fired* as vessels to enable it to keep its shape and be used in cooking and storage. The most commonly found ceramic therefore consists mostly of fired clay (or “earthenware”), possibly combined with other materials.

Ceramics are regularly made up of clay with other additions that have been deliberately, or accidentally, added to it. The most common deliberate addition to the clay is temper, which changes the properties of the clay during both firing and use. Temper can include sand, straw, rock fragments, ground-up broken ceramics (known as grog), and many other materials. The reason for the selection of a particular temper can be technological, for example, to reduce shrinking in drying and firing, but it can also be ritual.

Ceramic vessels can be shaped by hand-modeling, coiling, slabbing, molding, and throwing on various sorts of wheels (Orton, Tyers, and Vince 1993). Each of these techniques can leave traces in the appearance of the ceramic. This appearance can be changed once again by the firing process, which can change the color of the clay or even partially melt the ceramic body if fired at high enough temperatures.

The surface of the ceramics can be treated with different techniques to alter the properties of the ceramic (Orton et al. 1993). Commonly seen are relief, slips, and glazes (see GLAZES, SLIPS, AND PAINTS). It is very common for the surface of vessels to be decorated with incised patterns before firing. Also, prior to being fully dry, the surface of a ceramic can be polished before firing (known as burnishing), which results in a smoother surface. Another surface technique is to apply a very pure clay, painted onto the surface, or dipping the ceramic into it, known as a slip. A wash is a very thin slip layer that does not entirely coat a ceramic. Slips can be contrasting colors and can create polychrome vessels. A final possibility is to apply a glaze, which is commonly put onto the ceramic as a slurry and then fired to create a glass surface layer. Glazes are essentially a glass adhering to the surface of the ceramic, can have many colors and can themselves be painted (see GLAZES, SLIPS, AND PAINTS).

The abundance and ubiquity of ceramics on archaeological sites is the result of the wide availability of the raw materials for their production, the relative technological ease of making ceramics, their fragile nature and the limited options for

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reuse or recycling (Shortland and Degryse 2017). The fate of most broken ceramics is to be discarded. Most ceramics, however, especially fired ceramics, are very resistant to degradation when buried. Once discarded, they tend to pass relatively unchanged into the hands of the archaeologist, where a reconstruction of the shape of vessels or an identification of the raw materials used is possible. Research questions to be answered range from how and when ceramics were made, what they were used for, to where they were produced.

Typo-chronologies of ceramic vessels are studied on virtually every excavation worldwide, as the prime stratigraphic dating tool in archaeology (see *DATING IN ARCHAEOLOGY AND SERIATION*). Ceramics are also a proxy for the study of many archaeological questions, from craft organization and trade patterns, to social stratigraphy (presence of exotic goods), subsistence strategies (provenance of food based on the provenance of their containers, residue analysis on ceramic cooking pots and containers), and chronological changes in the standard of living (changing proportions of import versus local production). The identification and description of rare imported, foreign vessels or sherds in a mass of locally produced wares is perhaps traditionally the most important question asked in the study of ceramics. Non-local ceramics, because of the opportunity they give for the plotting of ancient trade and exchange networks, as well as the possibility of identifying high-status individuals or sites, are perhaps some of the most interesting parts of the analysis of this material. Moreover, the technology of producing ceramics, while in essence simple, varies through time and is adjusted by different societies. Material culture studies, in particular *chaîne opératoire* reconstructions, focus on different technological methods used to produce materials, alongside specifically studying human agency in making materials (see *MATERIAL AGENCY*). In essence, ceramic studies can range from studying which material was used to make a pot, to investigating which choices were made to make the ceramic significant in the framework of a particular time and culture (Arnold 2008). This has led to the discussion of the place of ceramic houses and their workers within society, and how the decisions they are

making both shapes and is shaped by the culture in which they are operating (Orton et al. 1993; Arnold 2008). Ceramics may serve as transmitters of information about their producer, owner and user, as they are part of a “material culture language” (Hodder 1986; Arnold 2008) (see *MATERIAL CULTURE*). Ceramics, therefore, are extremely useful both to the societies who have employed them, as well as to the scientists who study them.

Ceramics and archaeological sciences

As discussed above, ceramics analysis has been used to answer a range of questions, of which “how was it made”, “what was it used for” and “where was it made” are the most obvious ones (see *ARCHAEOLOGICAL SCIENCES*). It could be argued that for all archaeological artifactual evidence, the study of the provenance of raw materials, the production technology and trade of raw materials, and the study of formed artifacts must be based heavily on scientific analysis. As with the study of many material types, ceramics can be studied using a range of different equipment ranging from the naked eye or a hand lens to very expensive laboratory equipment, each of which gives different information of contrasting accuracy and reliability.

Pollard and Heron (2008) described the development of archaeological chemistry in detail (see *CHEMISTRY IN ARCHAEOLOGY*). In 1895, T. W. Richards published the first wet chemical analysis of archaeological ceramics in the form of Athenian pottery. However, in comparison with the well-established tradition of typo-chronological studies of archaeological materials, the more routine use of exact scientific tools has a fairly young tradition of research, mainly developed after World War II, closely related to the development of analytical techniques. Felts in 1942 microscopically studied ceramics excavated at Troy, but the most important archaeometric techniques for ceramological research were presented in 1956 by Anna Shepard and in 1970 by David Peacock. Since then, exact scientific techniques for ceramic studies have been used more and more frequently (and not only on ceramics, but on many different material categories).

A key concept in ceramic studies is that of *fabric* (Peacock 1977). The fabric analysis of a ceramic is the study and classification of this material based on the characteristics of the clay paste and their inclusions. This includes the color of the matrix, hardness, feel, nature of the fracture, firing process, production process, and the nature, amount, size and sorting of the inclusions. The resulting macroscopic groups are often referred to as wares: recurring combinations of distinctive attributes including color, temper, vessel form and type of decoration and techniques used (Henrickson 1994). After ceramics are sorted into groups by these relatively simple techniques, then the next stage is to try to characterize the groups. There are two main approaches to this: mineralogical and chemical. Often, the results of (macroscopic) fabric analysis are in perfect accordance with scientific studies. Nevertheless, in many cases a discrepancy between fabrics, wares and “petrographic wares” or geochemical groups is observed. While it is relatively easy to say that one group of ceramics is compositionally identical or different to another in terms of composition, it can be difficult to say *why* that might be so. This could be connected to the use of different clays, different temper or amount of temper, to clay processing or firing, and even the post-depositional environment and alteration.

Mineralogical approaches

The most common method of characterizing a group of ceramics is to examine its mineralogy. Thin-section petrography, a geological technique derived from the study and description of rocks, is still the main technique used for this (see PETROGRAPHY AND CERAMICS). Fragments of sherds are glued to a glass slide and polished down to a thickness of 30 μm , at which point most minerals in stone or ceramics become translucent. Under a polarizing light microscope, the minerals in the sample interact with the light going through them, generating colors and other properties characteristic of the minerals involved. As long as the ceramic is coarse-grained enough for the minerals to be visible, this is a very well established method for identifying raw material

mixtures used, formation processes, firing temperature, and oxidation state. It requires a good level of expertise and experience to be able to describe ceramic thin-sections, which, even to those geologically trained, can be difficult. Many textbooks and review papers exist on the basics of thin-section petrography in general, or ceramic petrology in particular (Reedy 2008; Quinn 2013; Braekmans and Degryse 2016).

Other possibilities for assessing the mineralogy of ceramics is to use scanning electron microscopy (SEM) or X-ray diffraction (XRD) (see XRD AND MATERIALS ANALYSIS). In SEM, minerals are identified by a combination of morphology and contrast or by using an attached energy dispersive spectrometer to analyze the composition of individual phases. It is possible to automate the identification of grains on the SEM, so that the whole section is mapped for different elements, and then grains that are the same are grouped together and counted. This can give good quantitative results for the mineral analysis of the ceramic or clay. Also in X-ray diffraction, next to identifying the nature of the mineral phases present in a sample, a quantification of the amount of these minerals present can be given.

None of the mineralogical techniques are suitable when the ceramic becomes too fine-grained (for petrography, that is when individual minerals can no longer be discerned), or too highly fired (for petrography, SEM and XRD: a large portion of the ceramic will melt into a glass, and the bulk mineralogy may change significantly), to have a recognizable mineralogy. In these cases, and to make a direct comparison to clay resources, chemical approaches have to be used.

Chemical approaches

A second major approach to the analysis of ceramics is to go from the optical, hand-specimen grouping to bulk chemical analysis. Where the early techniques of chemical analysis of ceramics used wet chemistry, this has now been superseded by an array of other techniques, especially atomic absorption spectrometry (AAS), neutron activation analysis (NAA) (see NEUTRON ACTIVATION ANALYSIS (NAA)), X-ray fluorescence (XRF) (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), optical emission spectroscopy (OES), and

inductively-coupled plasma (ICP) (see ICP-MS AND MATERIAL ANALYSIS) techniques (see INAA AND MATERIAL ANALYSIS and ICP-MS AND MATERIAL ANALYSIS) (e.g., Pollard and Heron 2008). To use these techniques, a sample is ground up and either dissolved in acid or pressed into a powder pellet and irradiated. The type of technique chosen for ceramic or clay analysis depends on which chemical elements are to be identified, and the likely concentrations. Bulk chemical analysis is possible for almost all elements, with detection limits for some techniques as low as parts per billion (ppb) or even parts per trillion (ppt). Chemical analysis, combined with statistical approaches (see STATISTICS IN ARCHAEOLOGY), can be very good at grouping ceramics and determining outliers (see STATISTICS IN ARCHAEOLOGY; POTTERY DATA QUANTIFICATION; and PRINCIPAL COMPONENT ANALYSIS). However, it does hide the detail of individual ceramic technologies in a way that mineralogical approaches do not.

Also, (semi) non-destructive techniques, which require no sampling and do (nearly) no damage to the object under investigation, are used regularly in ceramic studies (see NONDESTRUCTIVE COMPOSITIONAL ANALYSIS OF CERAMICS). While NAA is usually applied to powders to avoid possible heterogeneity in ceramics, it is in principle possible to irradiate a whole object and obtain very accurate trace element data. Also techniques such as portable XRF (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)) and laser ablation ICP have no or very little impact on a ceramic's integrity, and give a full array of major to trace element data (see INAA AND MATERIAL ANALYSIS and ICP-MS AND MATERIAL ANALYSIS). They are, however, surface techniques, and as such very sensitive to sample inhomogeneity. Moreover, calibration of pXRF to obtain (semi-) quantitative data is not always evident.

In pottery studies, it is assumed that the chemistry of sediments and ceramics made from them approximately reflects the main characteristics and the chemical properties of the rocks from which they were derived in the catchment area or geological system that provided them. This makes possible the direct comparison between the chemical characteristics of several likely clay resources and ceramic ware groups. Ethnographical studies of potters have shown that the raw

materials of ceramic production tend to be gathered very close to the kiln site, usually within a day's journey there and back (Arnold 2008). This means that the raw materials of local ceramics are derived very locally to the production site, and limits the number of clay resources that need to be investigated. Discarded, misfired sherds, known as wasters, are very useful for provenance studies, as these are often thrown away in situ, or in close proximity to the production site, after a failed firing process. They give an excellent idea of what wares the site was producing.

Just about every element of the Periodic Table has been used at some time to compare the typical composition of resource materials to that of archaeological artifacts. Depending on the nature of the materials analyzed (e.g., clay compared with ceramic), elements are chosen for their occurrence as major or trace elements and the nature of the geological-mineralogical information they provide. For example, aluminum, magnesium and potassium are typical major elements, which provide information on the type of clay minerals used. However, since most clays have similar, if not overlapping, major element compositions, there is little resolution in such analysis to distinguish different ceramic origins. The variation in trace elements, such as the transition metals or the rare earth elements (REEs), may then be much more useful in distinguishing between the different raw materials used. Overall, trace element analysis has been successful in answering archaeological questions on ceramic raw material provenance, recipes and manufacturing processes, and technological evolution.

Other approaches

In addition to the study of the ceramic itself to determine use, there is also the possibility of looking at residues within the pores of the ceramic, which may reflect what was held in a container or how a ceramic vessel was used (see FOOD RESIDUE ANALYSIS). This organic residue (see ORGANIC RESIDUE ANALYSIS) work can involve painstaking preparation and analysis of hundreds of potsherds over a wide geographical range. A wide range of biochemical components (biomarkers) including lipids and proteins derived from animal fats,

waxes, dairy products, and human remains can be preserved in and identified from pottery, and answer questions on diet, climate and subsistence (Degryse and Bentley 2017) (see DIET AND CARBON ISOTOPES; DIET AND NITROGEN ISOTOPES; DIET AND SULFUR ISOTOPES; and DIET AND TRACE ELEMENTS).

In the past decade(s), more unusual (rare and expensive) methods and equipment such as synchrotron radiation facilities have been used to look at archaeological ceramics. Recent developments also applied radiogenic isotope (see ISOTOPES) ratios to the analysis of pottery ($^{87}\text{Sr}/^{86}\text{Sr}$, $^{143}\text{Nd}/^{144}\text{Nd}$, $^{207}\text{Pb}/^{206}\text{Pb}$, etc.). It needs to be stated, however, that these studies are best carried out only when no other technique provides sufficient data for answering research questions (see SYNCHROTRON-BASED X-RAY ANALYTICAL TECHNIQUES AND MATERIALS ANALYSIS; X-RAY ABSORPTION SPECTROSCOPY (XAS, EXAFS, XANES); and NON-STABLE ISOTOPES IN ARCHAEOLOGY).

Ceramic characterization

There tends to be a hierarchy of techniques used in the analysis of ceramics, starting simply and cheaply with the bulk of the samples, and selecting smaller numbers at each stage to be subjected to analysis by more lengthy and expensive techniques (Shortland and Degryse 2017). Although providing a substantial amount of information on their own, the simultaneous use of several methods provides a more robust framework for interpreting ancient potteries. When time and money permits, a combination of petrographical and chemical approaches gives the best combination of information and is most likely to answer archaeological questions on provenance, trade and exchange, or use (Degryse and Braekmans 2014). The very ubiquity of ceramic finds on the majority of archaeological sites requires an investment in their study. A carefully constructed sampling strategy informed by clear questions and combined analytical techniques is essential to use ceramic characterization effectively as a method to unveil different aspects of our past.

SEE ALSO: Archaeological Sciences; Archaeometry; Chemistry in Archaeology; Dating in Archaeology; Diet and Carbon Isotopes; Diet and Nitrogen Isotopes; Diet and Sulfur Isotopes; Diet and Trace Elements; Food Residue Analysis; Glazes, Slips, and Paints; ICP-MS and Material Analysis; INAA and Material Analysis; Isotopes; Mass Spectrometry (MS); Material Agency; Material Culture; Neutron Activation Analysis (NAA); Nondestructive Compositional Analysis of Ceramics; Non-Stable Isotopes in Archaeology; Organic Residue Analysis; Petrography and Ceramics; Portable X-Ray Fluorescence Spectrometry (pXRF); Pottery Data Quantification; Principal Component Analysis; Seriation; Statistics in Archaeology; Synchrotron-Based X-Ray Analytical Techniques and Materials Analysis; X-Ray Absorption Spectroscopy (XAS, EXAFS, XANES); X-Ray Fluorescence Spectrometry (XRF); XRD and Materials Analysis

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Characterization of Metals and Alloys

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Metals are a group of inorganic, crystalline materials that can either occur naturally or result from the pyrotechnological processing of minerals. When found in metallic state in nature (i.e., not produced from ores by smelting), they are called native metals. Like all crystallized substances, metals are characterized and defined by their chemical composition and crystalline structure. Metals often contain only one chemical element with trace impurities (e.g., gold, copper, lead, aluminum). Their chemical content can be divided into “major” elements and “trace” elements. Major elements are those that define the material in question; they are usually measured as percentages and are commonly above 1 percent of the chemical composition of the material. Trace elements, on the other hand, are elements that occur in such small concentrations that they do not change the essence of the material; they usually have concentrations below 0.1 percent. In archaeology, trace elements are used primarily for provenance studies.

Ores are minerals (i.e., naturally occurring, inorganic, crystalline materials) that, when smelted, yield metals that have economic or social value for human societies. Smelting is a process by which an ore (one or more minerals that contain the metal) is heated, so that the metal in it is reduced to its metallic state and thus separated from the other chemical elements (Rapp 2000, 364–65). Some metals are alloys, that is, combinations of metals; for example, bronze is an alloy of copper and tin. This means that two or more different metals were melted or brought to liquid state, then mixed together. When the alloy cools, it has some of the properties of all the metals that were combined to form it. The discovery that a metal like copper, when combined with other substances, can acquire superior properties

apparently occurred in Southwest Asia around 3,500 BCE.

Metals, both pure and alloyed, have played a significant role in society throughout the ages. In ancient metallurgy, the transition from a copper technology to one based on bronze involved mixing copper with a range of arsenic-based compounds. The question here is whether these alloys were produced intentionally or were the accidental result of the composition of naturally occurring ores. Answering this question required characterizing (1) the metal objects unearthed by archaeologists, (2) slag (residues from smelting), and (3) the ores themselves. Hence our knowledge of the origins of copper-alloy metallurgy is largely indirect, as it derives from analyses and interpretations of the composition and structure of those materials (Rapp 2000).

The characterization of metals consists of the broad process of testing and measuring their structure and properties and the methods used to gather this information. This often involves techniques derived from archaeology, materials science, and geology for conducting chemical analyses, determining the sources of raw materials, and identifying ore-processing and metalworking techniques (Rapp 2000, 364). Scholars generally acknowledge the value of scientific and analytical techniques for increasing the information potential of archaeological findings by providing the framework for archaeometallurgy—the study of ancient and historical metallurgical technology that encompasses all aspects of metal production, from artifact manufacture to use and disposal (Pollard and Heron 1996).

Metals such as gold, silver, copper, tin, lead, and iron were among the earliest materials processed by ancient peoples. The vast majority of ancient metal artifacts, except for gold and platinum, were obtained by smelting metalliferous ores to produce different metals and alloys. Because of their continued use in and importance for modern society, great effort has been invested in learning about their synthesis, properties, and processing. Two major advances in the study of

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metals and alloys were brought about by the twin discovery that their microstructure was critical to their observed properties and that this structure could be modified by the processing history of the metal (Holloway and Vaidyanathan 2010).

Both the macroscopic external and the microscopic internal surfaces of metals and alloys are critical to their properties and performance in specific contexts. For example, ancient peoples often used metals like gold and silver, which were shiny and attractive, a practice still reflected today in the wearing of rings, bracelets, and earrings. The esthetic appeal of those metals results from their interaction with light, which depends crucially on their surface composition and topography. Analytical techniques have been developed that allow analyses of the top atom layer—or top 10 layers—of artifacts to determine why the reflection of light changed (Holloway and Vaidyanathan 2010, 1). The study of the metallographic structure of metal artifacts through different analytical techniques is well established and essential for understanding manufacturing processes.

Chemical properties of metals and alloys

Metals are highly reactive in most gaseous and liquid environments. Hence, for most of them, pure metallic forms rarely exist in nature; metals appear rather as oxides or minerals. This is why it is technologically and scientifically important to understand the chemical interactions of metals and alloys with the varied environments in which they were used. Given the importance of the surface and interface properties of metals, and also because crucial information is often hard to obtain, several tools have been developed to gather data. Each technique has significant advantages but also important limitations, and most can be used in straightforward or more sophisticated ways (Baer 2010).

The chemical properties of a metal surface are determined by analyzing such characteristics as composition, thickness, reaction (or growth) mechanism, and chemical and physical structure. Different analytical methods for examining surface and interface features can be used in a variety of ways to obtain distinct types of data. Valuable

results are often obtained when the analyst fully understands both the problem of interest and the technique used. The exact nature of the composition and structure of metals is critical for the method applied. In some cases, conducting the study requires intentionally modifying the surface composition. Modifying the surface is a key step in identifying specific properties related to the scientific study involved and the technology applied. The aim is to alter some property of the surface or region close to the surface of a material, but without degrading its “bulk” properties (Baer 2010, 43).

Different surface-sensitive methods of analysis provide information on the chemical properties of metals. There has always been a need for the creative application of diverse methods, which should maximize our insights into the chemical properties of metal surfaces. Fortunately, technological advances in current methods and the development of novel techniques are opening new opportunities for analysis. For example, surface analysis measurements are being increasingly combined with measurements obtained through chemical reaction techniques (Baer 2010). The scale of the structures observed during characterization ranges from angstroms, as in the imaging of individual atoms and chemical bonds, to centimeters, as when imaging coarse grain structures in metals (Leng 2008).

Characterization methods

The last two decades have witnessed major advances in the types of equipment available, the application of methods, old and new, enhanced to meet analytical needs. Areas of analysis that have seen significant development include decreases in beam size (i.e., finer area or volume of analysis), quantification (understanding of instrument characteristics and quantification methods), the elaboration of *in situ* methods (XRF, FTIR), improved databases, and the establishment of recognized procedures and standards. It is likely that the near future will see greater use of *in situ* real-time measurements in combination with well-established *ex situ* techniques (Baer 2010).

The process of characterizing metals and alloys for archaeological research depends on

the problem to be answered or resolved. Studies may focus on such issues as manufacturing technology, the origin of metal ores, smelting technology, casting techniques, gilding, corrosion, or authentication. Each one of these elements requires a distinct analytical approach (Rapp 2000, 365). Certain characterization techniques, such as basic optical microscopy, have been practiced for centuries, but new test instruments, methods, and methodologies are constantly being developed—and afterwards updated and improved. The introduction of the electron microscope and secondary ion mass spectrometry in the twentieth century, for instance, has revolutionized the field, for this technique allows the imaging and analysis of structures and compositions at much smaller scales than those reached by earlier methods. This has stimulated a great improvement of our understanding of the properties and behaviors of different materials.

Regarding the choice of analytical tools, there is no universal method for analyzing metals. No single technique holds all the answers; no method is necessarily the best in all situations, for all objects or problems. Nor can analyses be conducted using one sole approach, no matter how careful or creative it may be. Each case is specific and requires a different set of responses. The diverse forms of ores and mineral deposits entail that one particular element or suite of elements may constitute the critical distinguishing factor in some studies, though it may be irrelevant in others (Pollard and Bray 2014).

Nondestructive characterization techniques

Nondestructive testing methods have increased in importance in the study of archaeological objects. Among such methods, X-ray fluorescence (XRF) is perhaps the most popular one; and it is now available in the form of a portable handheld system. XRF offers considerable advantages because it can identify and quantify different metals simultaneously (Jenkins 1988). It is particularly well suited for identifying and quantifying metals and alloys, since most of the alloys used in antiquity (gold–silver, bronzes, and brasses) are made up primarily of heavy metals, which show up well under XRF. Of the metals known in ancient times,

however, iron is problematic, because the main alloying elements (carbon, phosphorus) are too light to be detected by XRF. The disadvantages of XRF thus include its lack of sensitivity when it comes to the smallest amount of a specific element that can be measured accurately.

In this context, proton-induced X-ray emission (PIXE) spectrometry emerged as a useful nondestructive analytical tool, which can simultaneously determine heavy and light oxides, as well as minor components. Recent instrumental developments in PIXE have resulted in highly focused proton beams (down to a few microns), which allow chemical analysis and elemental mapping on a microscopic scale. This technique is called microPIXE, or μ -PIXE. Variants of PIXE include particle- (or proton-)induced gamma-ray emission (PIGE), which can be used to detect some of the lighter elements that XRF or other methods do not detect (Pollard and Bray 2014). Ancient metals, especially alloys, however, are of a heterogeneous composition and contain a variety of phases, so PIXE analyses may not always produce representative results (Hauptmann 2007).

Semi-destructive characterization techniques

From an analytical perspective, better results are attained by removing a small sample from the metal object whenever that is possible, polishing it, and mounting it for analysis. This procedure allows further physical examination of the artifact (e.g., metallography, hardness) prior to any chemical analysis. Modern metal-characterization techniques can ascertain the levels of achievement of ancient metalsmiths (Pollard and Bray 2014). The microstructure of most metals used in antiquity preserves evidence of their thermal and mechanical history that can be observed easily with the metallographic microscope.

Evidence of work hardening (or strain hardening) and annealing is preserved in these microstructures. Metallurgists make wide use of the metallographic microscope in analyzing the structural features of metals and in identifying distinct compositional phases. Once a sample is taken, numerous options of analytical instrumentation are available for the characterization process. The two most common ones used

today are based on electron microscopy (EM) or inductively coupled plasma spectrometry (ICP). The metallographic microscope used in conjunction with the electron microscope can provide the structural and chemical analysis needed to address most archaeometallurgic problems (Rapp 2000).

Microscopy As a category of characterization techniques, microscopy probes and maps the surface and subsurface structure of materials—in this case, metals. These techniques can use photons, electrons, ions, or physical cantilever probes in order to gather data on the structure of a sample over a range of length scales. Common examples of microscopy instruments are optical microscopes and EM. For the last few decades, EM has been the most widely used technique for characterizing metals. While the microscopy side of the instrument employs a beam of electrons, the actual chemical analysis relies primarily on the detection of X-rays.

EM has many advantages. It can produce high-resolution images of the physical structures present, as well as micropoint chemical analyses and two-dimensional (2D) chemical maps of the exposed surface. This technique has been known by several names—for example electron microprobe analysis (EMPA), scanning electron microscopy (SEM), scanning electron microprobe with energy-dispersive spectrometry (SEM-EDS), SEM with wavelength-dispersive spectrometry (SEM-WDS)—depending on the particular configuration available. The disadvantage of nondestructive XRF is that it is a surface-only analysis with low sensitivity (Pollard and Bray 2014).

Spectroscopy Spectroscopy is a broad field with many subdisciplines, each with numerous implementations of specific spectroscopic techniques. These techniques are applied to investigate the chemical composition, composition variation, crystal structure, and photoelectric properties of metals and other materials. Some common instruments are energy-dispersive X-ray spectroscopy (EDX), wavelength-dispersive X-ray spectroscopy (WDX), X-ray diffraction (XRD), mass spectrometry, Fourier transform infrared spectroscopy (FTIR), and thermoluminescence

(TL). ICP is an especially sensitive quantitative analytical tool that measures the wavelength and intensity of the light emitted by a sample. It is used to detect trace elements as its primary goal but can usually detect many elements, down to the level of “parts per billion” (ppb, equal to 1 atom in 10⁹), from a very small specimen.

ICP requires that the elements to be analyzed be in solution, but more recently a device has been implemented that uses a pulsed laser to vaporize (ablate) a small volume from a solid sample into a gas stream, which then enters the plasma torch. This is known as laser ablation ICP (LA-ICP-OES). One disadvantage of ICP methods is that, while in theory all elements except argon can be determined, certain unstable elements require special facilities for the handling of the radioactive fumes from the plasma. Also, ICP has difficulty handling halogens, so a special optics is necessary for the transmission of very short wavelengths. The elemental analytical capabilities of most ICP techniques are comparable to, though somewhat better than, the data previously produced by neutron activation analysis (NAA), which had long been the preferred means of analyzing trace and ultratrace elements in archaeological and geological science (Pollard and Bray 2014).

Isotopic characterization of metallic archaeological artifacts

In addition to the chemical composition of a metal artifact, another major attribute that can be measured is the isotopic composition of its elements. Isotopes are atoms of a chemical element with the same atomic number and position in the periodic table and with nearly identical chemical behavior, but with different atomic masses and physical properties. Chemically speaking, the isotopes of an element behave identically, but sometimes take part in chemical reactions or physical transformations (e.g., evaporation) at slightly different rates. This is because the difference in mass of the isotopes means that the bond energy between one isotope and oxygen, for example, will be slightly different from that of another isotope with oxygen. Thus, over the course of various chemical reactions or transport phenomena, the ratio of one isotope to another of the same element may change. In the case of

chemical reactions, this is called fractionation. This means that the environmental or geological history of certain metals can be reconstructed by measuring isotopic ratios.

Almost all metals of interest to archaeometallurgy have more than one naturally occurring isotope. In fact, elements with only one isotope are exceptional in nature. The most relevant ones here are gold, which occurs naturally only as ^{197}Au , and arsenic (^{75}As). Many, such as copper (Cu, with the two isotopes listed above) and silver (^{107}Ag and ^{109}Ag) have a pair, but a significant number have several stable isotopes, for example iron (Fe, four), lead (Pb, four), nickel (Ni, five), zinc (Zn, five), and, topping them all, tin (Sn, ten). There is thus plenty of scope for measuring isotopic ratios among the metals of interest to archaeologists. By far the most intensively studied isotope is lead, with four stable isotopes, ^{204}Pb , ^{206}Pb , ^{207}Pb , and ^{208}Pb . The last three are the stable end members of the three long natural radioactive decay chains found in nature, starting with uranium (^{235}U and ^{238}U) and thorium (^{232}Th) (Pollard and Bray 2014).

Lead isotope analysis (LIA) is used in geoscience to understand the geological history of ore formation, but was rapidly adopted in archaeology, initially to assign lead and silver artifacts to a particular mining region or deposit. LIA was eventually accepted as a new and “secure” method for provenance studies of metal artifacts (Hauptmann 2007). LIA offers a sensitive analysis of masses in which isotope ratios are measured with a mass spectrometer. The decisive point that makes the LIA so valuable for provenance analyses is that lead isotope ratios do not change during metallurgical processes. The isotope pattern remains constant regardless of what temperature the ore is roasted at, under what reducing-oxidizing conditions the metal is smelted, or how often it is resmelted. Hence the pattern is characteristic of a particular deposit and allows a secure assignment of the finished product to the initial raw material (Pernicka 1987). Problems such as the mixing and reuse of metals from different sources, as well as limited reliable data and the contamination of samples, can, however, present difficult problems in interpreting LIA results (Budd et al. 1996). Bearing in mind the particularities of each case study, it is essential to link the chemical and isotopic



Figure 1 The Nebra Sky Disk, by Dbachmann, CC BY-SA 3.0. <https://commons.wikimedia.org/w/index.php?curid=1500795>.

characterization of metals around a systematic question and methodology.

Characterization of metals and alloys: A case study

One of the most significant cases in the field of the characterization of metals and alloys is the study of the Nebra Sky Disk. Found by two treasure hunters in 1999, this artifact displays the world's oldest known concrete depiction of astronomical phenomena (see Figure 1). Dating to 1600 BCE (Middle Bronze Age), this bronze disk is embossed with gold leaf symbols that appear to represent a crescent moon, the sun (or perhaps a full moon), stars, a curved gold band interpreted as a sun boat, and an additional gold band on the edge of the disk that probably represents one of the horizons. Another gold band originally located on the opposite side is missing. Given its somewhat obscure provenance, the disk has gone through a series of rigorous laboratory tests designed to prove its authenticity (Pásztor and Roslund 2007).

In addition to the question of the legitimacy and origin of this object and its raw materials, the analyses performed on the Nebra Sky Disk include in their focus the techniques of manufacture and the history of production that lie

behind it. Since its first impoundment in 2002, the disk has been thoroughly investigated by a number of research groups from different institutions. These analyses have included, among other methods, the chemical and physical characterization of the materials using X-ray fluorescence (XRF), synchrotron XRF, X-ray diffraction (XRD), computer tomography, isotope ratio mass spectrometry (IRMS), metallography, and both optical and scanning electron microscopy.

Important evidence for the authenticity and antiquity of the Nebra Sky Disk was provided by the Halle Institute for Archaeological Research in Germany. According to its findings, the copper used on the disk can be traced to a Bronze Age mine in the Austrian Alps. Tests have also indicated that a unique mixture of hard crystal malachite covers the artifact. Finally, microphotography of the corrosion on the disk has produced images that prove that it was a genuinely ancient artifact (see, e.g., Pernicka and Wunderlich 2002).

Concluding remarks

Archaeometallurgy deals with all the aspects of metal production, distribution, and usage in ancient and historical times. Resolving important research questions on metals and alloys often requires analysis at different scales. Scientific analyses of such materials are widely employed to measure the physical properties and to characterize the chemical composition of objects. A number of characterization techniques are used to examine external metal surfaces through the layers of corrosion that may cover the original metal. The exact characterization required for research on metals and alloys depends on the problems or questions to be answered or solved. Investigations tend to focus on issues such as smelting technology, manufacturing technology, casting techniques, gilding, corrosion, the provenance of metal ores, or authentication, each one of which will involve a distinct analytic approach.

SEE ALSO: Archaeological Sciences; Archaeology; Archaeometry; Archaeomineralogy; Chemistry in Archaeology; Compositional Data Analysis; ICP-MS and

Material Analysis; Ion Beam Analysis (PIXE/RBS); Metallography; Neutron Activation Analysis (NAA); Non-Stable Isotopes in Archaeology; Optical Microscopy; Optical Spectroscopies; Ore and Smelting Slag; PIXE and Material Analysis; Portable X-Ray Fluorescence Spectrometry (pXRF); Scanning Probe Microscopy; Synchrotron-Based X-Ray Analytical Techniques and Materials Analysis; X-Ray Fluorescence Spectrometry (XRF)

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Characterization of Petroglyphs

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The world's rock art can be conveniently divided into two principal components of roughly equal quantities—pictograms and petroglyphs. The former were created by an additive process, that is, material was added to a rock surface, while in the production of petroglyphs, material was removed from the rock. Consequently pictograms include rock paintings, stencils, prints, pigment drawings, and beeswax figures. Petroglyphs, made by a reductive process, include engravings, percussion petroglyphs, abraded petroglyphs, and finger flutings in caves (see various techniques in Figure 1). This division is useful because it corresponds not only to the two basic technological classes of rock art, but also to various methods of its study, for instance in age estimation or conservation science.

Another factor separating pictograms and petroglyphs is that the former rarely survive out of caves (see CAVES AND FISSURES) from the Pleistocene, whereas petroglyphs are more resistant to natural deterioration processes, particularly on weathering-resistant rock types such as granites and quartzite. Most of the world's surviving Pleistocene rock art consists of petroglyphs, especially where they are deeply pounded and relatively sheltered. In rare cases these may date from Middle Pleistocene traditions (in central India and the Kalahari Desert) but it is only with the last third of the Late Pleistocene that surviving petroglyphs become more frequent. The longevity of petroglyphs is proportional to the time it takes to create them. Replication has shown that the "composite hardness index" (the measure of a rock's resistance to compressive force) of a rock determines very decisively the production time of percussion petroglyphs. For instance, an identical petroglyph takes about 400 times as long to create

on unweathered quartzite as it takes on weathered sandstone (Bednarik 2016a). These differences are very pronounced, as are the potential survival rates of petroglyphs on different lithologies.

The two principal methods of removing rock mass in petroglyph production are by percussion or by an abrasive action. Impact can be direct, by a hammer-stone, or indirect, by a chisel-like tool combined with a hammer, but there is no ethnographic or replication evidence supporting the view that the second of these methods was applied. Abrasive-action petroglyphs were created by incision or by polishing a surface area. Most petroglyphs have been made with stone or metal tools, although on very soft rocks, bone tools have been used. Another technological separation is between petroglyphs rendered prominent through color contrast, by breaking through a thin surface veneer (patina or weathering zone), and those relying on relief for visibility (where the rock's surface and interior are of similar color). Technologically, the former group is defined as sgraffiti: made by the removal of a veneer to reveal the differently colored rock beneath.

The scientific study of petroglyphs delves primarily into their forensic analysis, that is, the recruitment of empirical evidence for determining the circumstances of their production and use. This includes information about the tools used in their creation, the recovery and study of such implements from sites of occurrence, the direction of tool application, the biomechanics and biokinetics of petroglyph production, identification of multiple applications of individual tools in abrasion petroglyphs, and the replicative studies required to translate such data into testable hypotheses. Another area of scientific concern is the taphonomy (see TAPHONOMY) of petroglyphs, which is intricately interwoven with their lithology, technology, and environmental variables (Bednarik 1994). Various phenomena connected with the characterization of petroglyphs derive from a range of disciplines, such as geology (e.g., the presence of kinetic energy metamorphosis products) or acoustics (e.g., concerning rock gongs, or the acoustic properties of

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Figure 1 Petroglyphs of various techniques, including one motif in the very rare negative petroglyph treatment, at Three Kings Site, Utah, USA.

sites), as well as many other fields. In view of the frequent inability of archaeologists to effectively discriminate between petroglyphs and natural rock markings of many types, another important consideration concerns the factors distinguishing exogrammatic from other rock markings that may resemble them, and their effective determination. Numerous types of natural markings occurring on rock surfaces can resemble petroglyphs, among them xenoliths, other petrographic marks, weathering and solution marks, tribological marks (e.g. by clastic movement), and rock marks produced by plants and animals. They and even utilitarian anthropogenic rock markings (e.g. drag marks, tool marks) have all been frequently misidentified as petroglyphs.

Dating of petroglyphs

One of the principal concerns in characterizing petroglyphs is the determination of their age. The strategies employed differ significantly from those applied to pictograms, because in contrast to them, there is no analyzable substance available that marks an image's antiquity. The rock mass removed in creating a petroglyph is not credibly recoverable, despite such efforts having been made. Therefore the range of methods engaged in estimating the antiquity of petroglyphs is unique. As in all dating work, the target date

(time of execution; Dunnell and Readhead 1988) is the preferred variable sought, but in the case of petroglyphs, only two methods have so far been applied to securing such results: microerosion analysis and patina colorimetry. Archaeological excavation, for instance, can only provide minimum ages, as does the quantification of fluvial erosion wear and surface retreat; or lichenometry, optically stimulated luminescence (OSL) analysis (see OPTICALLY STIMULATED LUMINESCENCE) or radiocarbon sampling of insect nests. Similarly, the determination of uranium-series products of carbonates or ferromanganese substances, the ^{14}C analysis of carbonates and oxalates, or cosmogenic radiation products (see COSMOGENIC DATING) only provides either minimum or maximum ages under favorable conditions. Cation ratio determination of accretionary mineral deposits has been rejected, and there are various problems with iconographic and stylistic claims about petroglyph age estimation. In short, the dating of petroglyphs remains notoriously complex, and both microerosion and colorimetry deliver only results with substantial tolerance ranges.

Nevertheless, microerosion analysis (Bednarik 1992) has provided numerous credible results from much of the world, and is being applied very successfully in China, Europe, Saudi Arabia (see Figure 2), and many other regions. In this noninvasive method, the geometry of wane formation along the edges of crystals fractured during the production of a petroglyph is utilized. The widths of these micro-wanes, visible only under a binocular microscope (see OPTICAL MICROSCOPY), are a direct and linear function of age. The rate of their development needs to be calibrated to the environmental conditions of specific regions and for particular minerals. So far, only quartz and feldspar have been used in this method, and only comparatively erosion-resistant rock types are of relevance. The calibration curves now available from many climatic regions have suggested that the rate of solution is primarily a function of precipitation and therefore the need for calibration is expected to fade out progressively. The results obtained through microerosion analysis are reliable, as there is no potential contamination, and reversal of the underlying process is impossible. However, the precision of results is relatively coarse, with tolerances of about 20 percent to 25 percent being reported.



Figure 2 Relief percussion petroglyphs, dated to the Neolithic period, at Jabal al-Raat, Shuwaymis, northern Saudi Arabia.

Colorimetry of the ferromanganese accretions formed on petroglyphs is another method striving to establish “target dates” without physical intervention (Bednarik 2009). However, this approach promises little in the way of precision and has so far only been applied experimentally.

Interpretation of petroglyphs

Unless there is sound ethnographic information available, the determination of the meaning of petroglyphs or other rock art lies outside of proper science. Nevertheless, it is the approach favored by most archaeologists and therefore requires attention. All iconographic interpretation (see INTERPRETATION) of rock art involves *pareidolia*, the experiencing of meaningful patterns in random stimuli. Since modern beholders of such imagery lack the brain structure and composition, and therefore the perception, of its producers (Helvenston 2013), the modern observers cannot determine the emic meaning of supposedly figurative motifs. We can only function as human beings in the context of our societies here and now; we have no way of understanding the conceptual world of people thousands of years ago.

Neurologically, the process of etic interpretation of rock art is the imposition of imagery stored in the visual cortex over the signals the lateral geniculate nucleus (LGN) of the thalamus receives from the optic nerve (Bednarik 2016b). As much as 95 percent of excitatory, inhibitory,

or modulatory input in the LGN derives from the visual cortex, superior colliculus, pretectum, thalamic reticular nuclei, local LGN interneurons and other projections. The latter include feedback projections from the higher areas of the visual cortex of the inferotemporal cortex, where visual memory and imagery occurs, back to the visual cortex. Therefore what we see is determined mostly by our internalized model of reality, and the ontogenic experiences stored in the brains of earlier humans who created rock art can be assumed to have been dramatically different from ours. Moreover, the “interpretations” of rock art decipherers cannot be tested; they are freestanding, capricious claims and are therefore not scientific.

In pareidolic interpretation of rock art the beholder divines the meaning of a motif by first deciding subliminally whether it is aniconic or iconic. If elements of the figure or its overall form convey the impression of being depictive it is perceived as iconic. The decoding of the motif is initially by disambiguation of marks and textures on a rock surface. The production of iconographic forms is simply the intentional creation of features prompting visual responses to a signifier; it induces visual ambiguity deliberately. The human visual system is prompted to perceive an object where only marks and textures exist, through exploiting their visual ambiguity. This is the basis of all iconographic art: its elements are arranged and rendered in such a way that visual disambiguation experiences them as resembling objects, via pareidolia. Once an arrangement of paint residues or grooves on rock is perceived as intended to depict an object, the arrangement is scanned for confirmation that one of the options presented by the visual cortex matches it in adequate detail to pursue the correspondence further. In this process any disconfirming visual aspects tend to be disregarded or explained away as not deliberate or as badly executed, as being attributable to awkward materials or deficient skills, or to stylization, conventionalization, or schematization. At this stage of the process science, demanding the full consideration of disconfirming evidence, is discarded in favor of confirmation and autosuggestion. The beholder has latched onto a potential interpretation and now rationalizes accordingly. Finally, the detected image is scanned for

arbitrarily selected “diagnostic details,” rendering the process nonscientific.

Formal characteristics

Another favored way of characterizing petroglyphs is to create taxonomies of them by defining formal categories. Although such an approach is essential for the quantification of assemblages, for their comparative assessment, for statistics and the definition of cultural entities, there are also considerable difficulties with such approaches. The range of motifs of a site does not present an inherently consistent system akin to the periodic table of elements; it can only be divided by arbitrary classification. Moreover, co-occurrence at a site does not imply that the components of a corpus belong to a single tradition. On the contrary, major rock art sites tend to be accumulations featuring the residue of multiple traditions, often prompted by pre-existing imagery. Unless these are recognized and separated, any taxonomy of motif forms serves little purpose and may be quite misleading. There is a tendency of believing to detect stylistic regularities, which are then proffered as evidence of culturally cohesive characteristics. This tends to lead to the circularity of the argument that such perceived formal consistencies have been demonstrated, and that they therefore reveal cultural diagnostics.

These are not the only adversities in creating etic taxonomies of rock art. The arbitrariness of the process is evident when the practicalities are considered in detail. For instance, one of the common petroglyph motif types is the circle, but there are in fact literally countless variations of the circle found in rock art. At what point should one discriminate between a circle and an oval? Is a circle made by a male the same motif as one created by a woman? Is a large circle the same motif as a small, a horizontal the same as a vertical? Are two circles two motifs or one? What if one is placed inside another one? The possible variations and combinations are endless, and wherever the analyst draws boundaries, these will always be arbitrary. Such etic taxonomies can be expected to differ from emic classifications and interpretations. Therefore they only serve as loosely

descriptive tools, they cannot be analytically valid and their scientific utility is very limited.

Not only must archaeological taxonomy be considered arbitrary, we have no way of knowing how the *surviving* evidence relates to the *originally* created rock art. How much rock art has fallen victim to patination, exfoliation, rain water, frost shattering, insolation, sediment cover, erosion, consulting archaeologists, or whatever other taphonomic factors? In short, formal characterization of a corpus of petroglyphs is of limited utility; its principal expediency is in the field of rock art conservation (see CONSERVATION).

Other scientific approaches

An important part of characterizing petroglyphs is the study of their technology, that is, how they were created. This is based on the methodology of forensic science, as is most of scientific work with rock art. The tribology of petroglyphs has only been considered most recently (Bednarik 2015) and this work has led to the discovery of kinetic energy metamorphosis (KEM) products in several continents. Replication studies of petroglyphs are inevitably involved in the investigation of their production methods, and they raise issues of biokinetics, energy investment, and the quantifiable empirical effects of petroglyph creation. Combined with inquiries into the taphonomy of petroglyphs and the application of forensic methods, this area of research has emerged as the most productive in generating credible scientific characterization of petroglyphs.

Another important aspect of the science of rock art is conservation science, a field that has been developed especially in the past 40 years or so. In the case of petroglyphs, it involves a good understanding of the lithology and the weathering processes they are subjected to. These include the effects of natural moisture (meteoric, capillary, through condensation, etc.), and physical and biological weathering. Alleviating these threats is the ultimate purpose of conservation work, and a variety of techniques have been developed. However, it needs to be clearly stated that the greatest threat to any rock art by far is human intervention, be it by site visitation, professional vandalism of archaeologists, or the incidental

introduction of environmental change. Concerning the latter variable, the most obvious factors are anthropogenic climate change and the universal global reduction of precipitation pH (acid rain).

Recording of petroglyphs

Traditionally, the recording of petroglyphs has been accomplished by a variety of methods, such as freehand drawing, photography, rubbing or stamping, tracing on transparent sheets, and by casting with such substances as latex and wax. There are shortcomings or significant conservation issues with all of these approaches, and more satisfactory in terms of results are night photography, using low-angle (“strafing”) lighting to provide better depth to photographs, and photogrammetry (see DIGITAL PHOTOGRAMMETRY). In the latter method, precise measurements can be taken and 2D or 3D models can be created from orthophotographs. Recent developments in the area of computer vision-based photogrammetry (see COMPUTER APPLICATIONS IN ARCHAEOLOGY) have resulted in a simplified methodology of generating such models from standard photographs, processing these with dedicated software (Sanz et al. 2010; Plets et al. 2012). The results permit 3D manipulation of digitized products, rendering the documentation not only more dynamic and precise, but offering a tool for scientific dissemination of results and also for the management of petroglyph sites (López Fraile, Gómez García, and Caballero Klink 2016). These developments have already begun to revolutionize the recording of petroglyphs and introduced hitherto unimaginable precision.

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Characterization of Pigments

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In ancient times, humans left their lifestyle marks in the form of rock paintings. Many of the cave paintings (e.g., in the caves of Altamira in Spain and Lascaux in France) represent different forms of simple handprints and wild animals. During the Paleolithic, humans used pigments available in their environment. Such pigments were inorganic minerals (earth pigments) and organic materials (soot or charred bones). The analytical investigation of ancient pigments is an important tool for understanding ancient materials, art history, and the development of technologies. Furthermore, the analysis of the painting materials helps in identifying a painting's technique and state of conservation before any restoration interventions. In the case of wall paintings, a number of analytical methods are regularly used. Microscopes (the optical, light-polarized microscope and the scanning electron microscope), elemental and microchemical analyses (by EDX and μ -XRF), and molecular analysis with μ -Raman and FT-IR spectroscopies are widely used.

Pigments in ancient Egypt

For decades, the ancient Egyptian pigments have attracted scientists and archaeologists. Pigment analysis is an important way of providing scholars with data on ancient materials and technologies. Pigments were used in ancient Egypt to decorate tombs, temples, coffins, pottery, and other funerary objects. Considered humanity's first synthetic pigment, Egyptian blue was a great technology used by the Egyptians for thousands of years. The main pigments used in ancient Egypt were of natural or synthetic origin. Earth minerals

and pigments derived from iron oxides were widely used in ancient Egypt. Red and yellow ochres (hematite, Fe_2O_3 ; goethite, $\alpha\text{-FeOOH}$) were used without interruption from the fifth dynasty (c. 2494–2345 BCE) to the Roman period in Egypt (El Goresy et al. 1986). For blue colors, the so-called Egyptian blue was successfully produced from the fourth dynasty on (c. 2613–2494 BCE). This pigment was made by mixing calcium salt (carbonate, sulfate, or hydroxide), copper compounds (oxide or malachite), sand (silica), and alkali flux materials (natron salts from Wadi Natrun, or soda-rich plant ashes). The final product is calcium copper silicate (cuprorivaite, $\text{CaCuSi}_4\text{O}_{10}$), a blue tabular crystal (about 15 μm to 30 μm in length). For green pigments, another form appeared shortly after the manufacture of Egyptian blue. Egyptian green is a multicomponent pigment, mainly of green wollastonite—a blue copper-, sodium-, and chlorine-bearing glass phase (Pagès-Camagna and Colinart 2003). For royal decorations arsenic-based pigments were used. Orpiment (As_2S_3), also known as king's yellow, was applied, with its shiny color, in wall decorations and coffins in ancient Egypt. Realgar (As_4S_4), with its red-to-red-orange color, was identified in the tomb of Thutmose IV (c. 1419–1386 BCE; El Goresy et al. 1986). In special cases, orpiment was added to ochre pigments in order to enhance the deep and shiny appearance of the color. The first evidence for these multi-pigmented layers in decorations was found in the Karnak temple complex (ruins of Hatshepsut, c. 1498–1483 BCE) and in the Deir el-Bahari temple on the west bank of Luxor, Egypt.

Another rare pigment, jarosite ($\text{KFe}_3^{+3}(\text{SO}_4)_2(\text{OH})_6$), was used to produce a pale yellow and was reported as a pigment in Egyptian contexts since the eleventh dynasty (c. 2133–1991 BCE). Furthermore, during the Ptolemaic and Roman periods in Egypt, green earths were used to decorate different monuments. These clay pigments are mainly based on the dioctahedral micas, celadonite, and glauconite. Earths of darker colors—usually called “sienna” and

“umber”—were probably used as pigments since ancient times. Their chromatic hues range from deep brown to reddish and greenish brown. They can contain admixtures of hematite and manganese (Mn III, Mn IV) oxides (Hradil, Grygar, and Hradilova 2003). Red lead (minium secundarium, Pb_3O_4) was found in Roman wall paintings in Egypt. It is one of the earliest artificially prepared pigments still in use until today. White pigments enjoyed extensive applications in ancient Egypt. It is believed that gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or anhydrite (CaSO_4) may be used from the fifth dynasty on. On the other hand, calcium carbonates were used until the reign of Emperor Tiberius (14 CE to 37 CE). Another white pigment, huntite ($\text{Mg}_3\text{Ca}(\text{CO}_3)_4$), was used for the first time in the New Kingdom (time of Hatshepsut or Tuthmosis III, c. 1504–1450 BCE; El Goresy et al. 1986). Also, hydrocerussite ($2\text{Pb}(\text{CO}_3)_2 \cdot \text{Pb}(\text{OH})_2$) was reported to have been found in the Ptolemaic baths near the Karnak temple complex, from the time of Ptolemy III (246–221 BCE). Black pigments of vegetable (plant matters, soot) or animal (charred animal bone and ivory) origin were used in ancient times. The most important pigment was carbon black, and the only crystalline carbon used as pigment material was graphite. Soot is famous for its fine crystals and its homogeneity; when mixed with the paint medium, these crystals appear in the form of chains or fibers. Black pigments from mineral sources such as manganese oxides were already identified as ancient pigments. Pyrolusite (MnO_2) was found in ancient Egyptian wall paintings from the twelfth dynasty (c. 1991–1786 BCE) in Beni Hassan tombs of the El-Minia governorate in Egypt.

The analytical techniques

The analysis of wall paintings is affected by many factors: the small size of sample, the degradation processes, the multilayered structure, and the complexity of the mixtures (which have organic and inorganic compounds). The analyzing method for ancient materials should be micro or nondestructive, fast, sensitive, and multielemental.

Optical microscopy (OM)

The examination of painting materials usually begins with visual observations that are useful in providing data about the stratigraphy of paint layers, their microstructure, grain size, and colors and in detecting any impurities. Paint flakes and mounted cross-sections are commonly used for that purpose. Samples must be collected from hidden or seriously damaged areas. A small part of the sample is mounted in plastic peel molds. Then the sample is fixed in vertical position by using a suitable adhesive (e.g., Acryloid B72). The sample is then placed on the sticky side of the tape, so that its “sandwich side” sticks in “standing” position on the tape. Epoxy resins or acrylic resins are used to mold over the sample and to cover it completely. The resins are applied at room temperature for 18–48 hours. The resin must be transparent, have a short hardening time, and be resistant to cracking; and it is best if it does not react with the sample. The last step is the process of polishing in special machines that use silicon carbide paper to obtain a perfectly flat plane and a full cross-section (Derrick, Souza, and Kieslich 1994). Siddall (2006) published an important review of the application of polarizing light microscopy to the study of pigments, plasters, and mortars from the Roman age.

A blue-paint layer was collected from the festival temple of Tuthmosis III (c. 1504–1450 BCE, the eighteenth dynasty). Preliminary observations on the sample were performed using an Olympus SZ-40 stereomicroscope. Microscopically, the sample showed a coarse heterogeneous matrix with dark and light blue colors. Diluted Egyptian blue pigment is fine-textured and a large amount of glass is formed in its composition.

Scanning electron microscopy

Scanning electron microscopy is widely used to investigate morphology, microstructure, and chemical composition, especially when combined with an energy-dispersive X-ray microanalysis detector (SEM-EDX). This technique uses a focused beam of high-energy electrons to generate a variety of signals at the sample's surface. These signals include secondary electrons that produce SEM images or backscattered electrons

that give BSE images. In SEM technique, samples are usually covered with a conductive coating, most often of carbon or gold. In environmental scanning electron microscope (ESEM), no preparation of the sample is needed. With computer-controlled instruments, X-ray colored maps are produced by recording the number of X-ray photons for a fixed time at each point in the scanned area.

A blue-pigment sample was collected from the wall paintings of the mortuary temple of Ramesses III (Medinet Habu, Luxor). The mortuary temple of Ramesses III (Medinet Habu) is one of the largest memorial temples in Egypt that remain from the twentieth dynasty. It was built at the order of the Pharaoh Ramesses III (c. 1184–1151 BCE). The sample was studied with a JEOL JSM-840A scanning electron microscope equipped with an energy-dispersive X-ray (EDS). Figure 1 shows an elemental map of a polished cross-section of the sample; the map was obtained through backscattered electrons (BSE). Idealized crystals of cuprorivaite can be easily noticed within siliceous coarse matrix. The element disruption microanalysis of the sample indicates that the predominant elements are silicon, calcium, and copper.

Micro X-ray fluorescence spectrometry (μ -XRF)

For some fifty years, X-ray fluorescence spectrometry has been applied successfully to the study of cultural heritage materials. This technique is working without consuming the samples and enables qualitative and quantitative analysis. This method is based on the excitation of an inner-shell electron by an incident photon in the X-ray region. During the deexcitation process, an electron is moving from a higher energy level to fill the vacancy. Then the energy difference between the two shells appears as an X-ray emitted by the atom. The X-ray spectrum acquired through this process reveals a number of characteristic peaks. Finally, the energy of the peaks leads to the identification of the elements, while their intensity provides the relevant or absolute elemental concentration (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)).

A sample of the blue-paint layers was collected from the wall decorations of the mortuary temple of Ramesses III (Medinet Habu) on the western bank of Luxor. The micro-XRF spectrometer (SPECTRO, COPRA model) was used to analyze the sample. The microanalysis of the sample indicates that the predominant elements are copper, silicon, calcium, iron, potassium with traces of magnesium, and chromium. With the aid of a micro-Raman spectrometer, these results indicated the presence of cuprorivaite in association with other compounds of quartz (SiO_2), gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), calcite (CaCO_3), and halite (NaCl). As for pigment samples from ancient Greece, Aloupi, Karydas, and Paradellis (2000) reported the capability of X-ray-based analytical techniques to study such samples from wall paintings and ceramics in Greece and Cyprus. Also, Egyptian blue was found in the palace of Knossos, which goes back as far as to the third millennium BCE (Filippakis, Perdikatsis, and Paradellis 1976).

Micro-Raman spectroscopy

Raman spectroscopy is a microanalytical method that offered many advantages in the analysis of heritage materials. It is a form of vibrational spectroscopy that allows the identification of particles in the micron order. The identification is based on the molecular vibrational spectra of the samples, obtained through excitation with visible laser light (see RAMAN SPECTROSCOPY). In a micro-Raman spectrometer, the laser beam is focused by means of microscope objectives that employ a backscattering configuration (Perardi, Zoppi, and Castellucci 2000).

Red-pigment samples were collected from Roman overpaintings at Luxor temple in Upper Egypt that date from the reign of the Emperor Diocletian (r. 284–305 CE). Raman spectra were recorded using a triple-grating spectrometer (Dilor XY) in the red line excitation (632.8 nm). The laser was focused on the sample through the microscopic unit attached to the instrument. The μ -Raman spectrum collected on a red-pigment sample that was compared with the RRUFF Raman-Database confirmed that the main characteristic bands (at 226, 298 and 408 cm^{-1}) are for

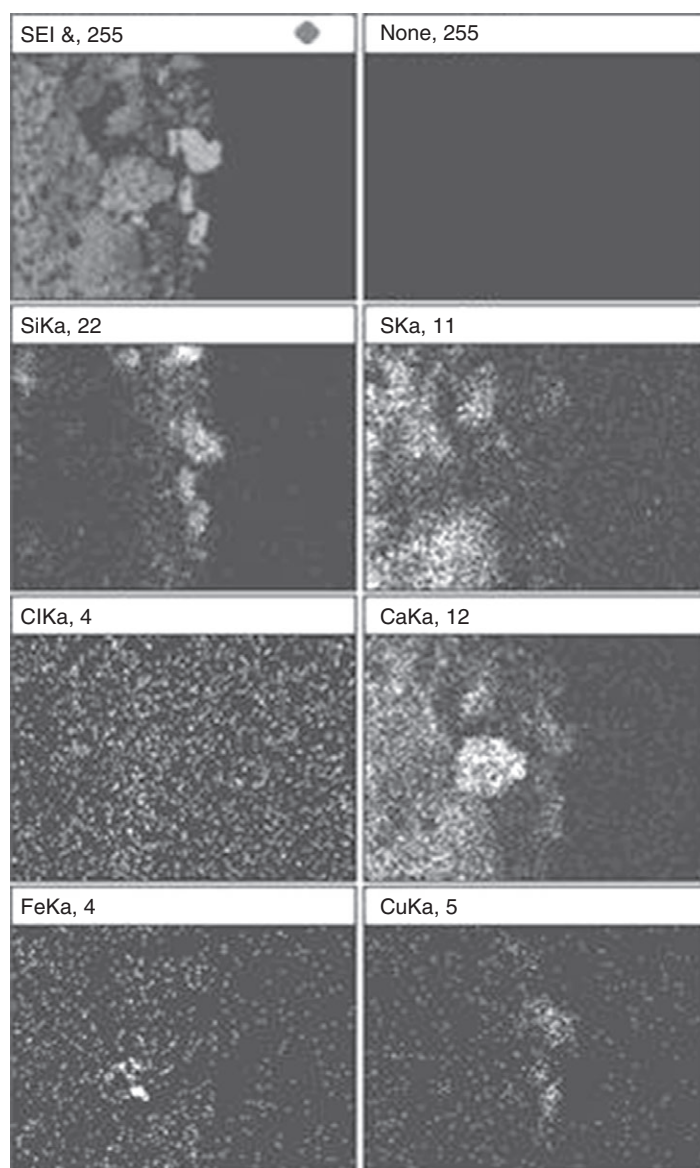


Figure 1 Backscattered SEM image and an element distribution map obtained from a polished cross-section of the blue-pigment sample from the mortuary temple of Ramesses III (Medinet Habu, Luxor).

hematite (Fe_2O_3). Moreover, Raman microspectroscopic analysis was applied successfully to the study of paintings in the hypocaust in the Roman villa of El Ruedo (Almedinilla, southern Spain), built in the first century CE. The specimens studied were from the third and fourth centuries (Mateos et al. 2015).

Fourier-transform infrared spectroscopy (FT-IR)

Infrared spectroscopy has a wide range of chemical applications. It helps in the identification of both organic and inorganic compounds. In this technique, the unknown sample is irradiated by

an infrared beam (IR). Then certain wavelengths that indicate the presence of specific functional groups are usually absorbed by the sample (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)).

Pigment samples were collected from the monastery of Saint Anthony in Egypt. The origins of the monastery date back to the fourth century CE. FTIR-ATR spectra were collected using a Perkin Elmer spectrometer 400. In attenuated total reflectance (ATR) spectroscopy, the sample is placed in contact with a special crystal (e.g., diamond, zinc selenide, germanium). The spectrum obtained on the green-pigment sample showed that green earths can be distinguished in the 3,400–3,700 cm^{-1} and 950–1,100 cm^{-1} range. Glauconite is characterized by broad peaks in the 1,100–944 cm^{-1} region.

Color measurements

Color measurements are applied to the study of painted objects for many purposes. They help in the registration of characteristic reflectance spectra. Measuring devices such as spectrophotometers and tristimulus colorimeters provide a numeric expression of the color that is based on mathematical conversions of tristimulus values. Also, measurement reproducibility is greatly affected by surface uniformity, which is significant because surfaces of wall paintings tend to be quite irregular. One of the most common numeric systems for expressing color or color difference is the CIELAB notation.

Pigment samples were collected from wall paintings in Egypt. The spectra were obtained in the visible wavelengths domain (400 to 700 nm) with the help of a Miniscan® XE Plus spectrophotometer. Chromatic values are expressed as color coordinates in the Commission Internationale de l'Éclairage (CIE) $L^*a^*b^*$ Color Space 1976 system. The reflectance spectra of the blue-pigment sample showed a slope at wavelengths higher than 650 nm, which indicates the presence of Egyptian blue. The green pigments sloped sharply at wavelengths higher than 630 nm, with values then continuing to increase after this wavelength. Some chromatic changes of the blue pigment in the form of green colors can be observed through a small shift (at 520 and 580 nm). The reflectance

spectra of the red pigment (hematite) showed a sharp positive slope at wavelengths higher than 600 nm, while goethite showed a slope lower than 600 nm. The reflectance spectra allowed researchers to identify and differentiate the colors of the samples and to detect any chromatic alterations.

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Chemical Mapping

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Definitions and introduction

The seemingly simple term “chemical mapping” actually encompasses a broad range of potential information that can be synthesized into a conceptual information-rich “map”. A chemical map for an artifact could contain chemical information such as composition, phase, and surface features that would translate into a multidimensional context for the object that includes geographical location, date, origin, function, and value. As may be imagined, chemical maps could include a wide range, with a nearly limitless variety of information. An important requirement, a boundary condition, is that chemical maps should provide an opportunity for new archaeological knowledge, interpretations, and insights. In this context, “chemistry” is synonymous with “chemical analysis”. This will effectively circumscribe “chemical mapping” with easily understood rules and boundaries (Guralnik 1984). This will be facilitated by a utilitarian classification of chemical substances having specific, albeit substantially overlapping, analytical techniques. The resulting data, for example, the concentrations of selected elements across an area of interest, would provide the basis of the chemical map. Chemical substances can be suitably subdivided into five interrelated classes, listed here with brief explanations and examples:

1. *Elements*: Fe, Co, Au, Pb, transition metals, lanthanides, and actinides.
2. *Molecules*: For example, indigo as found in Maya Blue pigments, where the indigo molecules form non-covalent or non-ionic bonds to the host palygorskite. The resulting composite material may be classified as a compound or possibly a mixture.
3. *Compounds*: Must have definite composition, represented by a molecular and/or empirical formula. Indigo, $C_{16}H_{10}N_2O_2$, is a molecular compound; palygorskite, $(Mg,Al)_2Si_4O_{10}(OH) \cdot 4H_2O$, is a compound but not a molecule; the rare white pigments laurionite, $Pb(OH)Cl$, and phosgenite, $Pb_2(Cl_2)CO_3$, have repeating units to form an extended structure that is not molecular.
4. *Mixtures*: Physical combinations of any proportion of elements, molecules, and compounds, where no chemical transformation takes place and the original identity of each is maintained; the chemical analysis can be similar to the analysis of the pure element, molecule, or compound.
5. *Materials*: This is the broadest category and used interchangeably with “solid-state” materials, whether organic (freshly-prepared gram quantities of indigo with varying levels of purity), inorganic (comprising “non-living” constituents such as galena, PbS), or biological (protein aggregates and oligosaccharides arranged by covalent bonding into large, cyclic tertiary structures).

Each chemical substance in this classification system will have a very large collection of applicable analytical characterization techniques with significant overlap and commonality, not unexpectedly, among the substances. Only three of the chemical substances are necessary to develop a useful definition for chemical mapping; these are *elements*, *compounds*, and *materials*. The general classification system and the simplification to three chemical substances will provide greater clarity within this article.

With three distinct solid chemical substances established, the fundamental definition of chemical mapping would combine the conventional geographical definition of “map” with the scope that “chemistry” encompasses. Webster’s Dictionary provides the necessary definitions (Guralnik 1984). The term “chemical” means of, or having to do with, chemistry. In turn, “chemistry” can be understood as the science that focuses on

the chemical elements (the Periodic Table), the compounds formed by the elements, and the associated solid-state materials. Seeking clarity from the night sky, *elements* have the same relationship to *compounds* that stars have to constellations. *Material* simply indicates the solid forms of elements and compounds. One of the great strengths of chemical analysis in relation to archaeology is that fundamental properties, atomic structure, for example, form the basis of most chemical analysis techniques. For example, XRD can be applied to almost all solid substances; archaeological meaning is obtained by combining and interpreting the analytical results with contextual information.

Within the field of archaeology, therefore, “chemical mapping” means the identification of chemical elements, compounds, and materials associated with an artifact, including trace quantities at part-per-million (ppm) levels. The elements become the stars, the compounds become the constellations. Like the unique arrangement of stars within constellations (created by human imagination), the presence and arrangement of elements within a compound or solid material can have additional meaning. In archaeology, this additional meaning can be knowledge and understanding about age, provenance, history, usage, relocation, and other contextual variables organized and understood through human imagination and experience. With continuing fundamental and technological advances, chemistry will become more integral to archaeology, and the scientific study of the life and culture of ancient peoples.

The natural and physical sciences are replete with techniques that can identify atoms and molecules in solids, liquids, and gases. Thus, it will be important and necessary that the term “chemical mapping” indicates the type of information being sought from the artifact under consideration. As might be imagined, based on the foregoing description, a wide range of subjects have been incorporated into chemical mapping. Some specific, representative subjects, combined with chemical mapping, will be described in subsequent sections of this article. In the meantime, two examples will demonstrate the most direct use of chemical mapping in a descriptive title: “Chemical Mapping of Paleontological and Archeological Artifacts with

Synchrotron X-Rays” (Bergmann, Manning, and Wogelius 2012) and “Chemical Mapping of Basalt Flows at Paleolithic Sites” (Goren-Inbar, Perlman, and Heimann 1986). Both of these titles provide a very useful precedent for chemical mapping publication titles: “Chemical Mapping of [Artifact Description] with [Analytical Technique]”.

In many cases, it is unnecessary to employ “chemical mapping” in a descriptive title, as demonstrated by: “Investigation of Neolithic ceramic pigments using synchrotron radiation X-ray diffraction” (technique abbreviation, SR-XRD). The analysis of artifacts with SR is a growing area of applied chemistry, and newly available techniques, generally abbreviated SR-XYZ (e.g. SR-XRF), are being applied to archaeological analyses. A large and expanding number of techniques can determine the elements, compounds, and materials within an artifact.

Mapping elements and compounds

A common analytical methodology is to map the elements of interest in a given area. This is exemplified by the mapping of elements in urban areas (Allen et al. 2011). Samples are obtained, digested, then analyzed by techniques that provide element concentrations, such as X-ray fluorescence spectrometry (XRF), inductively coupled plasma atomic emission spectrometry or mass spectrometry (ICP-AES or ICP-MS). Regarding the value of these elemental analysis techniques, the authors note: “These techniques are capable of determining up to 50 elements in a single analysis and have detection limits such that most elements can be determined and mapped at background concentrations” (Allen et al. 2011). Elements that can be identified include As, Cd, Cu, Mn, Ni, Pb, Se, and Zn.

Another modern-day example of chemical mapping utilizes a portable gas analyzer (developed in 2005) to characterize the gases emanating from a fumarolic field (0.045 km²). The output rates and relative ratios of CO₂/SO₂/H₂S were determined with 3,000 real-time measurements to produce a three-dimensional map of gas concentration from source to eventual dissipation.

Neutron activation analysis (NAA) was used to map 25 selected elements present in two very old basalt flows comprising an upper layer (233,000 years BP), an intermediate layer containing a Paleolithic site of great interest, and a lower layer (800,000 years BP). The authors indicate that “Those [samples] chosen for analysis represented all of the stratigraphic units described by the geologists, but with only 32 samples, the study must be considered exploratory. Nevertheless, it was hoped that it would serve to answer such questions as whether different units could be told apart and what further work would be needed to obtain a more comprehensive mapping” (Goren-Inbar et al. 1986). The study confirmed that element distributions obtained by NAA could be used to distinguish between two different basalt flows. Elements with a high crustal abundance were found at similar concentration levels (Ca, Fe, K, Na, Ti) in both basalt flows. However, the majority of the elements selected for analysis were at parts-per-million (ppm) levels. The upper and lower basalt flows did, indeed, have substantially different element distributions (within the ppm range).

Synchrotron radiation mapping techniques

An exceptionally wide range of archaeological artifacts have been analyzed, non-destructively, at various SR light sources around the world. The primary limitation with this technique is that artifacts must be transported to the SR facility. However, there is a long list of advantages, such as short analysis times (~1 min), small sample size or area, ability to analyze heterogeneous samples, high-intensity, tunable photon energy, high photon flux, high resolution, non-destructive, and the ability to process a large number of samples or sample multiple sites on a single object to provide statistical data.

SR dramatically improves the capabilities of existing X-ray techniques, such as X-ray powder diffraction (now abbreviated SR-XRD), X-ray fluorescence (SR-XRF), X-ray absorption spectroscopy (SR-XAS), near-edge X-ray absorption fine structure (SR-NEXAFS), X-ray absorption near-edge structure (SR-XANES),

X-ray photoelectron spectroscopy (SR-XPS), and others. Improvements are also observed for spectroscopic techniques like infrared absorption (abbreviated SR-IR), Raman scattering (SR-Raman), and many others (United States Department of Energy 2005). Although there are many techniques, they can be simply categorized as spectroscopy, scattering, and imaging.

SR-XRD was used to identify the mineral or material phases of black, red, and white pigments on the surface of Neolithic (~6300 BP) pottery sherds in much shorter times (30 s) compared with conventional XRD (hours) (Bugoi et al. 2008). The SR required only minute amounts of sample, so that a large number of samples could be analyzed. A small amount of material was removed from an unobtrusive location on a pottery sherd, sufficient to cover the backing tape on a 3-mm diameter 36-cell sample holder. The analyses produced very sharp diffraction patterns to unequivocally identify black jacobite (Fe_2MnO_4), magnetite (Fe_3O_4), and red hematite (Fe_2O_3). White pigments based on calcium silicates with high crystallization temperatures were also identified: diopside ($\text{CaMgSi}_2\text{O}_6$), augite ($((\text{Ca},\text{Na})(\text{Mg},\text{Fe},\text{Al})(\text{Al},\text{Si})_2\text{O}_6)$), and hedenbergite ($\text{CaFeSi}_2\text{O}_6$). The presence of white calcite (CaCO_3) was ascribed to post-burial deposition. Based on the outcome of this chemical mapping study, in the form of high-quality XRD patterns (the chemical analysis) across many samples (the mapping), the authors gained definitive information about clay composition, kiln atmosphere (several samples implied an unusual carbon monoxide-rich reducing environment based on the maintenance of magnetite during the firing process, although most samples were rich in hematite, Fe_2O_3 , indicating a typical oxidizing atmosphere), and the temperature reached (the presence of jacobite indicates a firing temperature of about 1,000 °C). Additionally, local sources were used for most of the minerals, but Mn-containing jacobite is uncommon and difficult to find. This led the authors to conclude: “This suggests that the Neolithic people specialized in gathering minerals from the surface of manganese mineral deposits and used them in producing black-decorated ceramics fired at high temperatures” (Bugoi et al. 2008).

Conclusions

As demonstrated in the few examples described in this article, chemical mapping takes many forms, but in all cases a chemical substance is analyzed and the resulting data are processed and interpreted to obtain new, often unexpected (as in the presence of jacobsite, Fe_2MnO_4 , in Neolithic pottery sherds) archaeological knowledge. The use of synchrotron-based characterization techniques will continue to grow in the coming years and begin to accelerate the amount of archaeological information already steadily increasing with each passing year.

SEE ALSO: Chemistry in Archaeology; Elemental Analysis of Pottery; Geoarchaeology; ICP-MS and Material Analysis; Neutron Activation Analysis (NAA); Raman Spectroscopy and Material Analysis; Synchrotron-Based X-Ray Analytical Techniques and Materials Analysis; TEM and Archaeological Materials; Transmission Electron Microscopy; Vibrational Spectroscopies; X-Ray Fluorescence Spectrometry (XRF); XRD and Materials Analysis

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Chemistry in Archaeology

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Chemistry is often referred to—at least by chemists—as “the central science” because of its position between physics and the life sciences. On one end of the chemical spectrum is physical chemistry, vital to understanding the processes involved in spectroscopic methods, while the biochemistry at the other provides the molecular basis of DNA and proteins. Thus chemistry is also central to archaeological science, playing a part in nearly every area covered by this *Encyclopedia*. Chemical analysis—elemental, isotopic, and molecular characterization—is arguably the most widely known connection between the seemingly disparate fields. More than just analysis, chemistry is also the study of changes in matter. Chemical processes, particularly oxidation, have profound effects on archaeological materials. Light, particularly that of ultraviolet wavelengths, induces chemical changes to fragile organic materials like textiles and paper, leading to fading and loss of structural integrity. Even some prospection methods rely on the presence of chemical species that form when people interact with the environment. Dating methods that rely primarily on physics—radiometric dating in particular—require an understanding of the chemical composition and possible changes to the material during deposition. The role of chemistry in archaeology reaches far beyond what can be addressed here. This briefest of summaries highlights only the most prominent aspects of archaeological chemistry and will neglect much; the reader is directed to the References and Further Reading.

The maturing field of chemistry and the infancy of archaeology both trace to the Age of Enlightenment, and in many cases begin to overlap soon thereafter as the eminent scientists of the day sought to understand the newly discovered

materials of the past. While Sir Humphry Davy's investigations into the composition of the pigments from Pompeii and Herculaneum may be the best known early application of archaeological chemistry, others before him applied gravimetric analysis to the compositions of metal artifacts in order to better understand the technologies of the ancients and even to try to reproduce them. An overview of the history of chemistry relevant to archaeology can be found elsewhere (Pollard, Heron, and Armitage 2016). In the twentieth century, instrumental methods, which are generally less labor intensive and in some cases nondestructive, mostly replaced the classical wet chemical analyses, albeit at the cost of some precision and accuracy.

The study of the exchange of materials, and thus the determination of their origin, is a more complex application of chemistry that seeks to answer questions of past human behavior beyond those of technology. The variations in usage of the terms “provenance” and “provenience” aside (Price and Burton 2011), the general idea is that the elemental composition of an object should be consistent with that of the geochemical source of origin. This provenance postulate can only be true if variations in elemental composition *within* a given source are smaller than the elemental variations *between* different sources. Ideally, it would be possible to “match” an object to its source, though really one cannot prove such a thing, only that an object is *not* associated with a source that is significantly different. Geochemical provenancing works best for objects made from unaltered natural material, like obsidian and some stone; in ceramics and metal artifacts, using elemental analysis to determine the source of the clay or ore may be complicated by mixing of raw materials from different sources. Quantitative measurements of multiple elements must be compared in provenance studies, so the preferred analytical techniques for such studies include neutron activation analysis (NAA), inductively coupled plasma mass spectrometry (ICP-MS), ICP atomic emission spectroscopy (ICP-AES, also called optical emission spectroscopy or OES),

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and X-ray fluorescence (XRF) spectroscopy. Atomic absorption spectroscopy, once a standard method, is only for sequential analysis of elements, and is not widely used in modern provenance studies. Many resources exist on geochemical analysis for provenance determination that provide further details (Glascok 2002).

Elemental analysis alone cannot determine the source of origin for all materials, particularly those that undergo recycling like metals and glass. In these cases, and in similar studies of human mobility, isotopic ratios of heavy elements have proven useful. While all atoms of a given element have the same number of protons, isotopes of the element differ in the number of neutrons present. Each isotope has a different mass equal to the sum of the numbers of protons and neutrons, and a mass spectrometer (usually ICP-MS specially configured for high mass resolution and high precision measurements) can be used to quantify each of the isotopes of interest. The isotopes of strontium vary in their geologic distribution, so the $^{87}\text{Sr}/^{86}\text{Sr}$ ratio in human teeth, for example, can be compared to local values to determine if a person was born in a different location from where he or she died. Strontium isotope studies have been widely applied to human remains as well as many other archaeological materials. Lead isotopes have been used to define ore fields and have shown utility in sourcing metal artifacts from around the world, and they, too, are applicable to a variety of objects. Isotopes of neodymium are useful as indicators of the source of sands used in the manufacture of glass. Combining measurements of multiple isotopes (e.g., Sr and Nd for glass) or with other analyses is often the best approach for such provenance studies.

Provenance determination has also been applied to organic “minerals” like amber and jet recovered from archaeological contexts. Fourier transform infrared spectroscopy (FTIR) has been used extensively to differentiate Baltic amber from other sources, which allows archaeologists to better understand trade routes for this organic gem across Europe in ancient times. FTIR and Raman spectroscopies provide information about molecular structure based on how covalent bonds vibrate when they absorb or scatter infrared and visible wavelengths of light. The two methods are complementary and can be used for the identification of both organic and

inorganic molecules. Additionally, both methods can be made portable, can be integrated with a microscope for work with small samples, and are generally considered noninvasive methods. Raman spectroscopy is widely used in the identification of inorganic mineral pigments in manuscripts and in wall and rock paintings. Due to the intensity of the laser source, fluorescence from organic molecules can sometimes mask the Raman spectrum. Organic colorants, particularly red anthraquinone compounds from madder and cochineal, can be identified in situ in natural textiles with the addition of nanoparticle substrates for surface-enhanced Raman spectroscopy. There are many comprehensive reviews on the uses of Raman spectroscopy for archaeological applications (e.g., Bersani et al. 2016). More frequently, identification of organic dye colorants present in archaeological textiles is accomplished by extracting the color into a solution which is then separated using high-performance liquid chromatography (HPLC), with the molecules detected as they elute from the column often based on how the molecules absorb ultraviolet and visible (UV-vis) wavelengths. MS, described above as a method for elemental analysis, can also be used to identify organic molecules, and so can serve as a detector in chromatographic separations as well as forming a *hyphenated method* (e.g., HPLC-MS). Molecules must be *ionized*—given a charge—for mass spectrometric analysis. *Soft ionization* methods, like electrospray ionization (ESI), provide information on the molecular mass of a substance and are often used in tandem with HPLC. For separating volatile compounds (or those that can be made volatile through chemical derivatization), gas chromatography (GC) is preferred. When GC is coupled to MS, the gas-phase molecules are ionized and fragmented with a *hard ionization* method like electron impact (EI) ionization as they elute from the column. The molecular ions or ionized fragments are characterized based on their mass-to-charge ratios, with the fragmentation pattern that results from hard ionization serving as a kind of “molecular fingerprint” for identification.

The origin of petroleum products can be determined using gas chromatography mass spectrometry (GC-MS); the relative amounts of various hydrocarbons differ depending upon the source, even providing a link to the biological

origin of the deposit. In archaeology, such studies have been applied to determining the sources of bitumen in adhesive residues on Near Eastern ceramics and Egyptian mummies. Molecules that originate from specific biological contexts are called *biomarkers*. While they were originally used by geologists to identify and differentiate petroleum deposits, biomarkers have revolutionized chemical analysis that seeks to understand human activities in the past (Evershed 2008). Using GC-MS to separate and identify biomarkers like abietic acid and retene, it is possible to identify resins as well as the pyrogenic products pitch and tar that are made from them. Lipids preserved within the ceramic matrix of cooking vessels may also serve as biomarkers that are indicative of specific foods that were consumed in the past. Residues from food preparation can also be preserved in earthen and plaster floors, indicating areas of food preparation and consumption, thereby shedding light on past human activities (Pecci, Barba, and Ortiz 2017). Identifying such biomarkers requires significant chemical preparation, from extraction of the residues into appropriate solvents to derivatization (chemically reacting fatty or resin acids to produce volatile methyl esters or trimethylsilyl ethers and esters), and then finally separation and identification by GC-MS. When identifying biomarkers, it is critical to always consider the archaeological context, as not doing so runs the risk of drawing conclusions that are not reasonable for the time and place!

In the case of lipid biomarkers, isotopes again provide a way to differentiate residues that cannot be distinguished based solely on their molecular composition. In organic molecules, the stable (i.e., not radioactive) isotopes of importance are those of hydrogen (^1H and ^2H , often called deuterium), carbon (^{12}C and ^{13}C), oxygen (^{17}O and ^{18}O), and nitrogen (^{14}N and ^{15}N). While the electrons in an atom are gained and lost the same way in a chemical reaction regardless of the mass of the nucleus, the energy required for the reaction to occur is higher for a heavier isotope relative to a lighter one, meaning that the product of the reaction will be enriched in the lighter isotope and depleted in the heavier one. This is called the *kinetic isotope effect* and explains why C3 plants that photosynthesize with a more complex set of chemical reactions show more *isotopic fractionation* than C4 plants that fix carbon more

efficiently. Fractionation is expressed as a ratio of ratios, comparing the ratio of the heavier to lighter isotopes relative to that of a standard. For carbon, this yields a $\delta^{13}\text{C}$ value in parts per thousand (per mille, ‰). Lipid residues in ceramics are generally dominated by palmitic and stearic acids ($\text{C}_{16:0}$ and $\text{C}_{18:0}$, respectively), which are both saturated fatty acids and by themselves are not particularly diagnostic. However, it is possible to include isotopic analysis with GC-MS, by way of gas chromatography combustion isotope ratio mass spectrometry (GC-C-IRMS), where each component from the GC is combusted to form CO_2 , which can then be used to measure the $\delta^{13}\text{C}$ value of that component. Because adipose fat and milk fat stem from different metabolic processes, their $\delta^{13}\text{C}$ values differ even when their lipid content appears quite similar, so GC-C-IRMS can differentiate between residues deriving from these sources, and thus the relative input of the different sources in ancient diets.

IRMS on light elements is widely used to study ancient diet, based on the idea that chemically, and therefore isotopically, you are what you eat (to a certain extent). In general, the $\delta^{13}\text{C}$ value measured for collagen, a protein preserved in bone, can differentiate between individuals with a diet rich in C3 versus those who consumed primarily C4 plants, which in North America is indicative of the introduction of maize. Nitrogen isotope fractionation is affected by trophic level, or position in the food chain, as the amount of ^{15}N increases up the chain from herbivores to carnivores. Measuring the $\delta^{15}\text{N}$ values of bone collagen can indicate whether or not ancient people ate seafood, which differs markedly from terrestrial food animals in $\delta^{15}\text{N}$ values. Hydrogen and oxygen isotope ratios are linked to the composition of locally available water sources. The $\delta^{18}\text{O}$ of human teeth, formed in childhood, can be used like strontium isotopes as indicators of outliers among a local population, showing individuals who moved to the area later in life (Pollard et al. 2016). Oxygen isotopes are also used in paleoclimate reconstruction. Evaporation and condensation of water, through physical changes of state, result in fractionation, with ^{18}O -rich water evaporating less readily and condensing more readily; the $\delta^{18}\text{O}$ values for water in polar ice cores decrease as a function of cooler temperatures. Hydrogen isotopes are similarly affected.

Bone collagen is perhaps the most important biomolecule in archaeological chemistry. Used in isotopic studies as above, it is also collagen that is preferred for radiocarbon dating of bone. Well-preserved bone collagen has been used to indicate the likelihood that reliable ancient DNA persists for analysis. Most recently, collagen has become the target for proteomic analysis, where the amino acid sequences of a protein are used to identify an organism down to the species level in many cases. Fragments of bone are often too small to identify visually; with proteomics, the collagen from such fragments can be extracted, then digested with enzymes to make shorter chains of amino acids (called peptides), and finally characterized with MS to yield a sequence unique to the organism. A new and promising approach to archaeological proteomics is called “zooarchaeology by mass spectrometry” or ZooMS (Collins et al. 2010). Small fragments of bone and egg shell can be identified with ZooMS, yielding information about exploitation of various food sources. Other proteins, like caseins from milk and hemoglobin from blood, that are preserved in residues can be characterized by proteomics methods as well. Combining several chemical methods, like residue analysis and proteomics, is often the best approach for small and fragmentary samples (Pollard et al. 2016, Chapter 13). Without the biomolecules preserved in a fragment of a finger bone and a few teeth, we would not know that the Denisovans even existed!

The future of chemistry in archaeology is nearly limitless, as analytical methods become more widely available, more user-friendly to the nonspecialist, less destructive to materials, and even field-portable. Even today, large datasets of elemental analyses and geographic information systems (GIS) are being put into combined use for understanding the movement of materials like metals across landscapes in ancient times (Hsu et al. 2016). Biomolecules that were once thought to be too fragile to survive will continue to provide new insights into human diet and resource exploitation thanks to advances in protein MS. MS itself has even undergone a revolution in how organic molecules both small and large can be ionized. Today it is possible to rapidly and without any extraction or sample preparation identify small molecules like dye colorants and food biomarkers in and on archaeological materials,

and often in such a minimally destructive manner that the materials can also be dated (Armitage and Jakes 2015) or preserved for future study. Hand-held portable instrumentation that is already commercially available allows archaeological scientists to collect both molecular and elemental information on objects in the field, and advances in miniaturization may yield portable techniques not yet considered possible.

This optimism for the future of chemistry in archaeology must also be tempered by the fact that the application of chemical analysis to ancient materials can never be presumed to be straightforward and simple. Methods developed for clinical analysis of fresh samples may be wholly inappropriate for ancient materials that have undergone myriad chemical and physical changes through time. As archaeologists cringe at the Hollywood depictions of Indiana Jones and his ilk, so too do chemists lament what passes for chemical analysis in the popular media, where magical boxes instantaneously produce not just results, but data interpretation and conclusions. The increasing prevalence of “point-and-shoot” instrumentation, particularly portable XRF spectrometers, has resulted in significant anxiety about the quality of data being published (Speakman and Shackley 2013), as well as whether users are aware of the limitations of both the method and the provided software (Shugar 2013). It is important to understand as much as possible both the nature of the materials and the capabilities and limitations of the analytical techniques before undertaking any analysis. As an example, analytical methods like XRF measure primarily the surface rather than the bulk composition of an object, due to the physics of the absorption and emission of the X-rays. For metal objects, analytical results can be influenced by surface corrosion as well as by enrichment or depletion of alloying metals at the surface. Selecting suitable samples and using proper techniques for their preparation is also essential. The importance of using traceable standard reference materials and applying appropriate calibration methods cannot be overstated. It is critical, too, that chemistry in archaeology be done not just in a scientifically responsible manner, but that it be driven towards generating data that will in some way address social, political, and economic questions about ancient people. Only then is chemistry really

useful to anthropological archaeologists who are seeking to understand culture and human behavior through material remains.

SEE ALSO: Archaeometry; Diet and Carbon Isotopes; Diet and Nitrogen Isotopes; Food Residue Analysis; Gas Chromatography–Mass Spectrometry (GC-MS); ICP-MS and Material Analysis; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Isotopes; Mass Spectrometry (MS); Mobility and Lead Isotopes; Mobility and Oxygen Isotopes; Mobility and Strontium Isotopes; Neutron Activation Analysis (NAA); Organic Residue Analysis; Portable X-Ray Fluorescence Spectrometry (pXRF); Vibrational Spectroscopies; X-Ray Fluorescence Spectrometry (XRF)

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Chert, Silex, and Obsidian Sourcing

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Archaeologists regularly find materials (e.g., minerals, pigments, metals, shell) on their sites, either in raw form or transformed into artifacts, that cannot be found in the local environment. Finding the geologic and geographic source or provenance of these raw materials can often be the key to understanding the territories exploited by groups in the past, or trade and exchange that took place between different societies. Finding the mines or quarries of these materials is also an essential element in exploring ancient technological knowledge and reconstructing the steps required in the production of certain artifacts. A detailed analysis of the sources of the raw materials often leads to better understanding of the choices (performance, durability, sharpness, transport cost) made by humans and their ancestors.

Research on the sources of chert, silex, and obsidian (CSO) has exploded since the 1970s. One reason is the fact that chipped stone tools are the oldest artifacts of human or hominin manufacture recovered on archaeological sites around the world. Stone tools are also very well preserved and therefore offer a unique insight into early human behavior. The increase in research specifically on the sources of stone tool raw materials is also due to the rapid increase in the access to various instruments for the geochemical analysis of these rocks and minerals. Archaeologists today have many analytical tools at their disposal to better characterize the rocks, such as CSO used to make tools and decorative objects in the past.

CSO are all siliceous rocks that break conchoidally. These clastic properties, as well as their hardness and ability to maintain an edge, are what have made these materials useful to humans for thousands of years. Chert is a siliceous rock that

can be formed in various geologic settings, but is usually sedimentary in origin. Chert is the most inclusive term, and can include chalcedonies and jaspers. The term chert is used mostly in North America. Silex is the term used primarily among non-English speakers for flint. Silex or flint is also of sedimentary origin and can be found as nodules replacing chalks and limestones. The formation and diagenesis of limestone-hosted cherts and flints is not completely understood and there is significant overlap between cherts and flints in their geologic origin as well as their physical and chemical properties (Fröhlich 2006; Luedtke 1992). Obsidian is a volcanic glass. In terms of its geochemistry, it can be classed as a rhyolite, which makes it quite different from chert and silex/flint (Poupeau, Le Bourdonnec, and Bellot-Gurlet 2014; Shackley 1998). Several other siliceous rocks have been used in the past to manufacture tools and decorative objects (e.g., quartzite, rhyolite, agate); the techniques described below apply to the study of all sources of siliceous rocks.

Sources

Archaeologists define a source of raw material as a geologic outcrop or a secondary deposit of material (e.g., river cobbles, glacial till). Evidence of past quarrying or mining is not always obvious at these sources of materials. If people have used cobbles from a river, the only evidence might be the cobble cortex still present on tools or production waste like flakes. Paleolithic quarries are in fact extremely rare due in part to the soft nature of the limestone or chalk bedrock and the time that has lapsed since their exploitation. In general, it is via the workshops where people transformed the raw materials that we can often discover the original geologic source of a material. By the Neolithic period, people were excavating mine tunnels to extract silex/flint at places like Brandon, England, and Spiennes, Belgium. Here, specialists chipped and ground the silex into axes for local use, and also for export and trade across western Europe. In many cases,

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the quarrying activity of successive generations destroys the evidence of previous quarrying or mining activity. The extensive piles of debris, mostly flakes and low-quality host bedrock, are the best indicators that a source of CSO has been used over many generations. Ancient quarries are also notorious for not being easy to date, since there are rarely any diagnostic artifacts found among the millions of pieces of debris.

Where an actual quarry or mine can be identified, the archaeologist can clearly see how materials were selected and how the gangue was rejected. This helps to narrow the variability of the raw material source at the geologic outcrop. The material selection will also help to understand technological choices made by ancient flintknappers and stone workers. In many cases, however, clear evidence of a quarry is lacking and the archaeologist has to either focus on the workshops close to the geologic outcrops, or carry out geoarchaeological fieldwork using bedrock or surficial geology maps to identify the most likely formations and member (see *GEOARCHAEOLOGY*). A source in this case becomes a geologic formation that can often cover many square kilometers. In the case of obsidian flows, these can often be differentiated in the field, but they can also cover large areas.

Characterizing a source of CSO

Once a source has been identified, the raw materials need to be characterized. In the case of rocks and minerals, this usually begins with thin-section petrographic analysis. This is the traditional geologic approach to characterizing rocks and minerals, and is the best method for identifying any characteristic fossils, minerals, or structures in the rock (e.g., Eley and von Bitter 1989; Reedy 2009). All of these petrographic characteristics help to narrow down the source in terms of a member or bed within a formation. This also helps to understand the mechanical characteristics of the material that may influence the transformation or performance of the material (e.g., cleavage, foliation, joints). Obsidian is a glass and therefore does not have a crystalline structure. For this reason, petrographic thin sections are not often used in characterizing obsidians. Petrography

can help nonetheless in identifying phenocrysts or other distinguishing aspects of an obsidian.

Once the petrographic analysis has been completed, the next step is to characterize the source material using a geochemical or imagery technique. A number of instruments and techniques can be used to characterize CSO, and most sourcing studies combine a number of complementary techniques. These are constantly evolving and the field of archaeological science has to adapt to these new techniques with their various limitations and advantages. The most common instruments and techniques are described below, but first it is important to address the issue of sampling.

Sampling and sourcing studies

Perhaps the biggest challenge in the field of sourcing CSO is sampling. How does one sample a source in order to have a representative sample that covers the geochemical or petrographic variability of that source? In some cases, like that of an obsidian flow, the geochemical variability may be minimal, allowing the sampling to be more limited. In other cases, like that of chert formations that extend for kilometers, this can be much more difficult to assess in the field. Silex or flint is usually present as nodules in beds, and specific beds were targeted in the past for exploitation. This can also help to narrow the sampling strategy. Typically, the geochemical characterization of a source will have to proceed in steps. First, one does an initial sampling of a formation or member along and across strike. These samples are then analyzed to assess the chemical variability of the raw material source. If this variability is high for several elements, then it may be difficult to differentiate which specific part of a formation was used unless this is clearly related to a specific location along strike (related to a basin, for example) or across strike (a specific bed or member within a formation). The same problem can arise if the chemical or petrographic variability is minimal. In this case, it might be impossible for an archaeologist to identify a source more precisely than a very large area several square kilometers in extent that is covered by a geologic formation.

Techniques and instruments used to characterize CSO

The techniques used to characterize CSO can be divided into two categories: chemical and imagery. Chemical techniques analyze either the chemical composition of the rock and its constituent minerals (major, minor, and trace elements) or specific isotopes. Imagery techniques create images of the rocks and minerals at high magnification using the interactions of electrons and the surface of the material. Petrography is an imagery technique that is based on transmitted light microscopy using polarized light and filters. All of these techniques make use of instruments that are housed in specialized laboratories. In some cases, like the scanning electron microscope combined with an X-ray spectrometer, chemical and imagery techniques can be combined in one instrument. Some techniques are destructive, requiring samples to be reduced to powder, others are microdestructive, such as those that use a laser to remove a tiny sample from the surface, and other techniques can be applied in a completely nondestructive fashion.

Most instruments can produce qualitative and quantitative data, and how these are used depends on the research question being addressed. In addition, each instrument has different levels of precision, accuracy, and limits of detection. In terms of chemical characterization this can vary for each element being measured. The lack of international certified geochemical standards for CSO makes it difficult to develop reliable, interlaboratory tests for precision, accuracy, and limits of detection.

CSO have different levels of intrasource chemical variability which affects how an instrument will be applied to the analysis of samples and artifacts. Obsidian is the most homogeneous and an analysis taken anywhere on an artifact or hand sample will typically be representative of the whole artifact or geologic sample. On the other hand, cherts are highly variable even at the level of a hand sample. This is due to their sedimentary origin. As a result, when carrying out chemical analyses it is important to keep in mind this chemical variability and analyze more than one location on an artifact or geologic sample in order to counter what is referred to as the nugget effect.

The following instruments are those used most often for the sourcing of siliceous rocks in archaeology.

Neutron activation analysis

Neutron activation analysis (NAA) (see NEUTRON ACTIVATION ANALYSIS (NAA)) or instrumental neutron activation analysis (INAA) (see INAA AND MATERIAL ANALYSIS) has been used extensively for the chemical characterization of obsidian, and to a lesser extent chert and silex. It was one of the first techniques used to characterize obsidians and link geologic sources to artifacts found on sites (Griffin, Gordus, and Wright 1969; Renfrew, Dixon, and Cann 1966). It has the advantage of measuring a large number of elements simultaneously (>30), and has very low limits of detection for many elements (parts per million to parts per billion) such as trace elements and rare earths that are typically important for identifying the geologic source of a rock. The technique can be used in a nondestructive mode if the artifact fits in the polyethylene vial.

X-ray fluorescence spectroscopy

X-ray fluorescence spectroscopy (XRF) (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)) has also been used extensively for the chemical characterization of obsidian, and to a lesser extent chert and silex (Shackley 1998; 2011). It can be used nondestructively, and has the advantage of being able to analyze large artifacts that will not fit in other instruments. It has proven particularly well adapted to the analysis of obsidian due to the homogeneous, noncrystalline (glass) structure of obsidian. The advent of portable XRF (pXRF) (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)) has added an important new dimension to sourcing studies, giving the archaeologist the possibility of analyzing artifacts in the field or in a museum. This is especially useful where the artifacts cannot leave a country or a secure setting. The precision and accuracy of the latest XRF and pXRF instruments is excellent. Limits of detection for many elements are only at the 10s of ppm for most instruments, unless they are equipped with a powerful X-ray tube and a vacuum chamber.

Particle-induced X-ray emission

Particle-induced X-ray emission (PIXE) (see ION BEAM ANALYSIS (PIXE/RBS) and PIXE AND MATERIAL ANALYSIS) is similar to XRF but uses a particle beam to excite the elements in a sample. The detection system is similar to NAA and XRF, and precision, accuracy, and limits of detection are comparable, depending on whether the sample is analyzed in a vacuum or not. PIXE has been used less than NAA and XRF for sourcing CSO because of the limited number of beam lines available on particle accelerators which tend to be in universities and museums (e.g., Accélérateur Grand Louvre d'Analyses Élémentaires (AGLAE)). PIXE can provide a much finer resolution of the sample area analyzed, since the beam line can be focused down to a few micrometers in width. Newer synchrotron accelerators (see SYNCHROTRON-BASED X-RAY ANALYTICAL TECHNIQUES AND MATERIALS ANALYSIS) may provide added possibilities for chemical and physical analyses of rocks and minerals, but to date their application in sourcing CSO has been very limited.

X-ray diffraction

X-ray diffraction (XRD) has traditionally been used in geology to identify the mineral constituents of rocks. As a result, it is a well-established and proven technique. XRD requires a sample to be reduced to a powder, which has limited its application to archaeological artifacts, but, in some cases, artifacts made of stone such as beads can be analyzed nondestructively using a special sample mount and low X-ray incident angles. XRD is not suitable for analyzing obsidian because it requires a crystalline structure.

Inductively coupled plasma

Inductively coupled plasma (ICP) instruments (see ICP-MS AND MATERIAL ANALYSIS) are routinely used in geochemical analyses and are increasingly becoming the standard for archaeological sourcing applications for a variety of materials. In order to deliver the sample to the ICP torch, CSO can be ablated using a laser, or it can be powdered and digested in acids and then analyzed

in solution mode. ICP instruments are then combined with a detector that can quantify either the component chemical elements or specific isotopes (see ISOTOPES). Depending on whether the focus is on specific chemical elements or isotopes, or the complete suite of elements potentially present in a sample, the ICP can be combined with a variety of spectrometers: AAS and OES, or MS (see MASS SPECTROMETRY (MS)). ICP instruments have very low limits of detection, which allows them to measure essentially all of the elements of the periodic table in the parts per billion range or even lower. In addition, the microdestructive aspect makes these instruments particularly attractive for archaeological artifact analysis.

Scanning electron microscope

The scanning electron microscope (SEM) is a versatile imagery instrument that can allow the archaeologist to visualize rocks in different ways (see ELECTRON MICROSCOPY IN CONSERVATION). This gives a better understanding of the mineral make-up of the rock, and how its structure might be characteristic of a CSO. In most cases, SEMs are equipped with an XRF spectrometer which enables the researcher to analyze the chemical make-up of the constituent minerals. SEMs have the advantage of allowing for a higher resolution in the analysis of the rock surface.

Petrography

Petrography is a standard technique for the identification and characterization of CSO. It is destructive, which limits its application to artifacts, but it is an essential step in narrowing the potential geologic universe of a source and correctly identifying a rock. Cherts and silex are relatively easy to differentiate based on fossils and other minerals or structures, which makes this a powerful technique (see also PETROGRAPHY AND CERAMICS).

Linking an artifact found on a site with the source of its raw material

The ultimate goal of sourcing research is to link an artifact found on an archaeological site with the original source of the raw material that was

used to make it, and perhaps to the workshop where this material was transformed. The tens of thousands of CSO artifacts found on archaeological sites around the world attest to the fact that people often traveled great distances to obtain these valuable materials. In other cases, they exchanged goods for these raw materials, or the objects made out of them. The archaeologist can therefore use the data from sourcing studies to reconstruct past territories or trade networks. The primary challenge in reconstructing these past movements remains primarily at the sourcing end. In other words, the quality of the data available for each source of CSO that is known will greatly influence the success that an archaeological scientist has in terms of linking an artifact to its source.

In some cases, the source is simply not known. After more than 50 years of intensive geochemical characterization studies on the obsidians of Mesoamerica, the US Southwest, and the Eastern Mediterranean, researchers in each of these regions still find new sources of obsidian among their artifacts that cannot be linked to a known source based on their chemistry. The case is even more striking in many parts of the world where people used cherts and other widely available siliceous rocks. The sheer magnitude and extent of the geologic formations that house potential sources often makes it impractical to even initiate the sourcing research and this has seriously hampered the development of research in many regions. In terms of silex or flint, the geologic sources of western Europe are largely known and have been studied primarily using micropaleontology. But even in this case, widely separated sources of silex/flint can contain the same fossils, making it difficult to differentiate them and therefore identify the precise source of an artifact. While the instruments and techniques for sourcing continue to improve, their application to sourcing CSO remains constrained by the challenges of sampling the potential geologic universe and the geographic scale of the archaeological research question.

SEE ALSO: Archaeologies of Technology; Archaeomineralogy; Elemental Analysis of Pottery; Infrared Absorption Spectroscopy (IR,

FTIR, DRIFT, ATR); Obsidian Hydration Dating; Petrography and Ceramics; Raman Spectroscopy; Raman Spectroscopy and Material Analysis; XRD and Materials Analysis

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Chromatography and Archaeological Materials Analysis

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Introduction

Chromatography is essential for the study of archaeological organic materials. Since most archaeological organic substances comprise complex mixtures of molecules with a wide range of chemical and physical properties, chromatography's analytical utility is essential to modern archaeological research practice and more broadly to cultural heritage studies. Identifying and characterizing the compositions of archaeological organic mixtures helps archaeologists to interpret ancient people's lifestyles.

Organic materials recovered in archaeological contexts are composed of a mixture of molecules. Chromatography allows us to separate and identify these molecules, being a technique that "allows separating a mixture into its individual components and simultaneously determine quantitatively the amount of each component" (Scott 1995). It allows us to analyze gaseous, liquid, or solid samples, and the analysis can be carried out with expensive instruments or simple techniques.

The word chromatography derives from the Greek words for "color" and "writing." It owes its name to the Russian botanist Mijaíl Tswett, who first employed the technique at the beginning of the twentieth century to separate plant pigments. Chromatography has since developed rapidly and is now used for different separation processes of molecules. In 1952, Martin and Synge, who established the principles of modern chromatography, received a joint Nobel Prize in Chemistry for their contribution to the "invention of partition chromatography."

Chromatographic separation is achieved by distributing the substances to be separated between a moving phase (the so-called *mobile phase* which can be a gas or a liquid) and a *stationary phase* (a solid, or a liquid supported on a solid). In a simplified vision of the technique, the mobile phase flows through the stationary phase and carries the components of the mixture with it, while the stationary phase retains them.

The various constituents of the mixture travel at different speeds—based on differences in characteristics, such as their molecular weight and structure, as well as on their affinities to the stationary and mobile phases—and reach the end of the chromatographic system at different times (it is said that molecules "elute" with different "retention times"). These different speeds of "elution" allow us to separate the mixture into its constituents. The separation processes that use a gas as the mobile phase are called "gas chromatography," while the processes that use a liquid are called "liquid chromatography."

Samples of archaeological materials (e.g., resin, pitch, beeswax, dung, organic residues trapped in ceramic vessels) are usually analyzed as organic solutions and therefore must be extracted by a solvent before their analysis. Depending on the objectives of the analyses and the materials analyzed, different extraction methods can be followed. Chromatographic analysis includes different techniques such as gas chromatography (GC), high-temperature gas chromatography (HTGC), liquid chromatography (LC), and pyrolysis/gas chromatography. Gas chromatography (GC) (see GAS CHROMATOGRAPHY–MASS SPECTROMETRY (GC-MS)) is commonly used, but it is unsuitable for the analysis of high-molecular-weight biopolymers or proteins. Bigger molecules, such as triacylglycerols, can be identified by techniques such as HTGC. In pyrolysis GC, the sample is rapidly heated, and large molecules are fragmented into volatile particles that are later separated by GC. In LC, the mobile phase is a liquid. High-performance liquid chromatography (HPLC) utilizes a high pressure and for this reason is called also high-pressure liquid chromatography.

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Chromatography gives better results when it is coupled with mass spectrometry, a highly selective, specific, and sensitive technique that separates ions according to their mass charge (m/z) ratios. Combined, the two techniques allow for the reliable identification and characterization of a mixture of components. GC can be coupled with isotopic analyses in gas chromatography combustion isotope ratio mass spectrometry (GC-C-IRMS) to identify the relative ratio of stable isotopes of carbon, hydrogen, nitrogen, or oxygen in individual compounds and to pinpoint the origin of such substances (Evershed 2008). In combination with accelerator mass spectrometry (AMS), chromatography can make it possible to date the organic residues preserved in the samples (Berstan et al. 2008).

Prior to applying chromatographic techniques, it is important to establish whether or not the samples require any treatment prior to the analysis; which are the most suitable for extraction, derivatization, and analytical methods; and which instruments best suit the analysis of specific materials and best align with the objectives of the research. In archaeological research, good results depend on the application of specific techniques and sampling strategies.

Application

The application of chromatographic techniques to the study of ancient materials has opened new paths in the investigation of different fields, such as the identification of ancient tars, resins, pitches, and incenses, as well as of ancient dyes such as indigo; the understanding of the use and function of ceramic vessels, pipes, and stone tools; the function of rooms and buildings; and the identification of activity areas. These methods have also provided evidence for the early domestication of animals and plants, the introduction of specific foodstuffs in human diets, and the historic consumption of alcoholic beverages and drugs. More broadly, they have yielded information about food practices and diets in different archaeological sites and cultures. Chromatography has also allowed archaeologists to explain ancient production processes and technologies and to ascertain the degradation processes of different substances.

This knowledge has enabled the conservation of ancient materials, and, in some cases, it has been able to identify their forgery.

One of the most important applications of chromatography is the identification of organic residues (amorphous or absorbed by porous materials), which are usually preserved as a mixture of substances (see ORGANIC RESIDUE ANALYSIS). Cooking pots likely contained different foodstuffs. Many substances ended up on kitchen or temple floors while cooking or performing ritual activities. Different oils and animal fats might have been burnt as fuel in ancient lamps. Beeswax and resin might have been mixed to produce a glue; and amphorae containing wine or oil might have been coated with pitch. The possibilities yielded by chromatographic techniques to recognize these various materials have existed since the 1970s, when these were used to investigate amphorae contents and lamp fuels (Condamine et al. 1976).

The difficulty of identifying residues of wine, which, along with oil and fish sauces, was one of the most important commodities traded in the ancient world, has long hindered the study of amphorae contents. However, recent developments in the identification of wine residues with LC and GC coupled to mass spectrometry have given new impetus to this line of research. They have made it possible to study wine's origins, its production and consumption at different sites, and its use as an offering for the dead and for gods. The consumption of other beverages, such as pulque, chicha, and black drink (a pre-Columbian North American beverage), as well as chocolate and beer has also been established thanks to the identification of specific biomarkers through chromatographic techniques.

Lipids are among the compounds more commonly identified in organic residue analyses (Evershed 2008). By studying their distribution and isotopic signature, it is possible to establish the various species of animals consumed in different areas of the world, to distinguish between adipose fats and dairy products, and to identify evidence of ancient dairy product consumption. Proteins can also be identified with chromatographic techniques—albeit with due care in interpretation—and their study gives clues regarding many interesting aspects of

ancient daily life. Proteins are often well preserved in dental calculus, and their recognition facilitates a deeper understanding of food consumption in different regions and periods.

In recent decades, organic residues analysis carried out by chromatographic techniques has concentrated mainly on the analysis of ceramic materials. However, the technique can be used to identify residues preserved in other porous materials, such as the plaster used to make floors in different areas of the world or to make the coatings of vats from production installations for wine, oil, or fish by-products. The analysis of such materials has often been carried out by means of spot tests, and the combination of spot tests with GC has helped to interpret data and to produce knowledge about the function of rooms, buildings, production structures, and spaces in general (Pecci 2013; Pecci, Cau, and Garnier 2013).

Chromatographic techniques have also been applied in the analysis of beaten earth floors, fireplaces, anthropogenic soils, and ancient cultivation fields, as well as in the identification of dung traces in the archaeological record. They likewise play a crucial role in the characterization of amorphous materials such as beeswax, resin, pitch, incenses, tars, bitumen, and gums. These are found as bulk materials transported and preserved in ancient vessels, such as incense burnt during rituals, as waterproof linings of vessels, boats, or buildings; as glues used to repair ceramics or to make other artifacts such as knives, projectile points, masks, and many other ritual and domestic tools; and as glues for body and teeth decoration. Such substances can also be identified in the pores of ceramic matrices, since they were used as waterproofing agents in ceramic vessels and as preservatives and flavorings. Chromatographic analysis sheds light on the use of these materials, their production processes, and their geographic origins (Stern et al. 2008).

Chromatography has found many more applications. It has been used to characterize fossil resins such as amber and to identify the polymers used to imitate these materials and others (such as precious stones). It can characterize waterlogged archaeological wood, making it possible to determine degradation processes and to develop consolidation and conservation procedures

(Colombini et al. 2007). Finally, the application of chromatographic analyses to cultural heritage can identify the original techniques used to paint and glue and the substances used in previous conservation processes.

Future directions

Chemical analyses in archaeological research should always be conducted in collaboration with a team comprising historians, archaeologists, chemists, archaeozoologists, and materials specialists such as botanists in order to accurately understand the materials investigated (and the degradation processes that they have undergone) and to contextualize the results obtained. The interpretation of chemical results must take into account the archaeological contexts where materials were recovered and answer the historical and archaeological questions that prompted the analyses. Likewise, ethnoarchaeology and experimental archaeology should be integrated in the study to better identify the archaeological substances investigated, their use, and their production processes.

SEE ALSO: Bioarchaeology; Food Residue Analysis; Mass Spectrometry (MS); Soil Chemistry in Archaeology

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Clay Tablets

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Cuneiform is a system of writing first developed by the ancient Sumerians in Mesopotamia during the fourth millennium BCE. The name comes from the Latin word *cuneus* for “wedge” owing to the wedge-shaped style of writing. The canvas for writing in cuneiform script was soft clay, onto which a stylus was pressed to form wedge-like word-signs. It is estimated that between half a million and two million cuneiform tablets have been found in modern times, of which only less than 100,000 have been read. Hence, cuneiform tablets form immense collections of hundreds of thousands of documents, representing the dynamics of cultural interactions and literary processes of the Ancient Near East (ANE) during the third, second, and first millennia BCE. This period constitutes the heyday of the great empires from the Early to the Late Bronze Age, which gave birth to the compilation of the great corpora of the ancient world. This period witnessed the production and dissemination of a large quantity and variety of textual materials written upon clay tablets by means of the cuneiform script in several languages (Akkadian, Sumerian, Hittite, Hurrian, and Northwest/West Semitic dialects). These textual materials dealt with matters of state, administration, law, religious life, literature, economy, magic, medicine, and the art of divination.

For nearly a century, the study of clay tablets was restricted only to Assyriologists, who devoted their studies to historical, linguistic, paleographic, and epigraphic aspects of the script. Only in the 1970s it was noted that clay tablets may be approached from an entirely different angle, through scientific analysis of their clay. By applying the protocols used for chemical and mineralogical composition of ceramics (see *CHARACTERIZATION OF CERAMICS*), the problem of locating the provenance of ANE clay cuneiform

tablets can be addressed. Such studies, employing neutron activation analysis (NAA) (see *NEUTRON ACTIVATION ANALYSIS (NAA)*), were first made to tackle the identification of specific toponyms (Artzy, Perlman, and Asaro 1976). However, despite some informative results, this approach was discontinued. Only towards the turn of the twenty-first century and with this notion in mind, several comprehensive studies have been conducted (Goren, Finkelstein, and Na'aman 2004). Through petrographic (see *PETROGRAPHY AND CERAMICS*), inductively coupled plasma mass spectrometry (ICP-MS) (see *ICP-MS AND MATERIAL ANALYSIS*), and NAA studies of samples from documents from the Amarna archive, Ras Shamra-Ugarit, Boğazköy-Hattuša, Babylon, several cities in Palestine and Israel, and Cyprus, these studies aimed at pinpointing the technology and geographic origin of tablets, thus clarifying the geographical history of the ANE. The theoretical basis for such studies lies in the fact that archives of cuneiform texts contain numerous tablets whose origin is unknown. Letters often contain the name of the sender, but sometimes the letterhead is partly or entirely missing; in other cases, we may have the name of the sender and still ignore his domicile. Worst of all, the location of some ANE countries and towns has not yet been clearly established. Moreover, documents other than letters might be assigned to an origin only by their style or location of discovery, but this may remain a matter of dispute. In such cases, scholars can only hope to find some paleographical, linguistic, or thematic clues for the origin of a document.

This methodology enabled for the first time scientifically based provenance study of hundreds of clay cuneiform tablets, using mineralogical and elemental methods. While the former identified the minerals in the clay and temper of the tablet, the latter used diverse analytical techniques to measure the concentrations of the elements in the clay. These studies have demonstrated firstly that cuneiform tablets were not always produced of the same clay types as the local pottery; hence they should be treated separately from other archaeological ceramics. Second, while

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pottery can be usually studied by the routine mineralogical and elemental methods involving intrusive sampling, clay tablets are unique and delicate and the sampling, if allowed at all, should be much below the standards of the regular petrographic and elemental examination procedures. Therefore, the main effort must be directed to the development of new methodologies, with the support of nondestructive techniques (see NONDESTRUCTIVE COMPOSITIONAL ANALYSIS OF CERAMICS). As Goren, Mommsen, and Klinger (2011) have shown, these are suited for the analysis of large numbers of clay tablets in museums and collections using portable apparatus such as portable X-ray fluorescence (pXRF), Raman spectroscopy (see RAMAN SPECTROSCOPY AND MATERIAL ANALYSIS), and surface Fourier transform infrared spectroscopy (FTIR) (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)). If a museum having collections of tablets is equipped with an environmental scanning electron microscope with attached electron dispersive X-ray spectroscopy (ESEM-EDS), formation processes of the tablets can be made without extracting samples (Cartwright and Tylor 2011). The results of these nonintrusive methods can be manipulated on location and compared with an existing database of clay compositions of cuneiform tablets. This can serve to select samples for further mineralogical (petrographic) study,

to be extracted by minimal sampling techniques (Goren et al. 2004, 4–12) and processed if needed on location using a portable petrographic laboratory. In turn, the leftovers from their preparation process can be used for a further set of analytical techniques for the determination of clay mineralogy by X-ray diffraction (XRD) (see XRD AND MATERIALS ANALYSIS), the determination of firing temperatures by thermogravimetric analysis, and absolute dating by archaeomagnetic intensity (see ARCHAEOMAGNETIC DATING OF BAKED CLAY FEATURES).

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Dyes

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Dyes or colorants are organic substances dissolved in solution when applied to a substrate. The attachment of the dye to the substrate is achieved through chemical interactions or physical entrapment processes. Dyes are regularly used to color fibers (see FIBERS), so they are expected to be found on textiles (see TEXTILES); but they have also been used to color leather, furs, feathers, wood, paper, and parchment. In the past, dyestuffs were extracted from a great variety of sources: flowers, leaves, barks, fruits, roots, lichens, mushrooms, insects, and molluscs.

In traditional textile dyeing, colorants are divided into three groups, according to the dyeing procedure: direct dyes are applied to the fiber substrate directly; vat dyes need to go through a chemical reduction process that transforms the colorant into a soluble precursor before dyeing; and mordant dyes are fixed to the fibers with the aid of metal ions called mordants, which act as bridges between the dye and the fibers, creating chemical bonds. Dyes may become pigments (see CHARACTERIZATION OF PIGMENTS) by being precipitated onto an insoluble inert substrate such as clay, hydrated alumina, or chalk; and then they are called lake pigments. Pigments, on the other hand, are organic or inorganic insoluble, finely grinded, and colored particles that need a binder in order to be fixed onto the substrate's surface.

Dyes may also be classified by their chemical structure. The main chemical groups found in nature are quinones, flavonoids, carotenoids, indigos, and tannins. Anthraquinoid dyes are the most important subgroup of the quinones. Their sources vary in nature: they are present in the roots of different madder species (*Rubia* spp.) or in the bodies of scale insects such as Mexican, Polish, or Armenian cochineal (*Dactylopius coccus*, *Porphyrophora polonica*, and *Porphyrophora hamelii*, respectively), lac (*Kerria lacca*),

and kermes (*Kermes vermilio*). Flavonoids are responsible for most yellow dyes, but may yield a wide array of different hues. Reds from the heartwoods of sapan and brazilwoods (*Caesalpinia sapan*, *Caesalpinia brasiliensis*, *Haematoxylon brasiletto*) belong to a subgroup of the family called homoisoflavonoids. Less firm yellows, such as carotenoids and curcumins, are also used for dyeing and painting. For example, the orangey-red of annatto or achiote (*Bixa orellana*) is used by Amazonian people to decorate their bodies, and the Mayans of Yucatan use it to color food. Indigoids yield very stable, even permanent blues and purples. The first are extracted from different plant sources around the world; the second come from sea snails and were exploited by different ancient groups along the Mediterranean and Pacific coasts of North and South America.

Dye sources that produce stable, lightfast colors are few. Before William Henry Perkin's discovery of the first aniline in 1856, good-quality dyestuffs were in high demand; they were considered luxury goods and many of them had to be imported from faraway lands. Since the beginning of the Middle Ages, Europe's most important manufacturing centers bought silk fibers and textiles along with indigo, redwoods, and insect dyes from the Far East and India through the Silk Route—a network of trade routes that connected Europe with the Far East via Asia Minor; it existed since around the third century BC and continued until 1453, when the Ottomans in Constantinople blocked relations with the West. Commercial routes promoted connections between people, and therefore the coexistence and merging of cultures in terms of art, religion, politics, language, philosophy, science, and technology, as well in terms of the trade of material goods.

The conquest of the New World gave the Spanish and the Portuguese crowns the opportunity to introduce a whole new group of dyeing sources into the Eurasian markets. Mexican cochineal (*Dactylopius coccus* Costa), along with various species of dyewoods (redwood, *Haematoxylon brasiletto*; logwood, *Haematoxylon campechianum*; old fustic, *Maclura tinctoria*; brazilwood,

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Caesalpinia brasiliensis) and indigo-producing plants (mainly *Indigofera suffruticosa*), began to be exploited and merchandized soon after the conquest and Spain's subsequent expansion into Aztec territory. Due to its great color yield, the Mexican cochineal became Spain's second most priced good after silver.

The characterization of the materials out of which the objects of our world heritage are constituted begins to unfold, as multitechnique strategies and methodologies are brought together for their study. Our understanding of the differential use of colorants and pigments—that is, of the procedures and technologies used in their manufacture and application as dyes (e.g., on fabrics) or as paints (e.g., on canvas) has developed profoundly thanks to a combination of scientific and humanistic skills: archaeometry (see *ARCHAEOLOGY*), archaeology (see *ARCHAEOLOGIES OF TECHNOLOGY*), art history, biology, conservation science (see *CONSERVATION SCIENCE*), chemistry, ethnography (see *ETHNOGRAPHY AND QUALITATIVE METHODS IN THE FIELD*), physics, and technical art history are some of the professions that join in collaborative projects dedicated to the study of the past. The combination of archival investigation, experimental reconstructions, fieldwork, and scientific analyses of both reconstructed and original samples has become a regular procedure.

The material evidence that survives from the past consists largely of examples of unique and precious objects that were used on special occasions and with particular intentions: representations of deities or ancestors, votive offerings, the attire of religious and political authorities, military uniforms, clothes of wealthy men and women, and so on. For this reason they were safeguarded with the utmost care, both during their serving lives and after. Analytical studies of both textiles and works of art from the past confirm the use of precious materials for their confection. We may assume that local coloring sources were also amply employed, but the lack of written documentation and precludes the possibility of using reference materials in our analyses, which makes the identification of these sources quite difficult.

The clash of cultures in subjugated territories led the victors to the discovery and exploitation of materials until then unknown to them. The incorporation of new supplies often prompted

the craftsmen to adapt new methods and working techniques. The observations recorded by Francisco Hernández (c. 1515–87) in his *Historia natural de Nueva España* (*Natural History of New Spain*) and by Bernardino de Sahagún (1499–1590) in his *Historia general de las cosas de Nueva España* (*General History of the Things of New Spain*) on how the Nahua people used dyestuffs for dyeing and painting are a good example. Hernández was commissioned by Philip II of Spain to document the natural richness of the newfound kingdom. He had to pay special attention to the cataloguing of plants with medical properties and to record the illnesses they were used for, how they were prepared, the form in which they had to be applied or taken, and the efficiency of their use. Many of the dyestuffs he recorded had medicinal properties; but Hernández also noticed the impact that the exploitation of such materials could have on the crown, given the economical significance of the European textile industry. Sahagún explains that his interest in recording things related to the natural realm is mainly philological. As a mendicant friar, his primary concern was to understand the indigenous way of thought in order to guarantee the conversion of the pagans. He was convinced that language was the most reliable tool for true communication among people and for their understanding of one another. His chapter on color (chapter 11 in Book 11 of his *General History*) incorporates recipes for the preparation of lake pigments and dyes. It is evident that his closeness to the indigenous scribes who helped him carry out his investigation and illustrate his manuscripts made him more appreciative of the importance and possibilities of lake pigment manufacture.

For many reasons, the information regarding the sources and preparation techniques of dyes and pigments is invaluable for archaeologists, art historians, ethnographers, and conservators who try to decipher the body of material culture (see *MATERIAL CULTURE*). They need to establish the provenance of objects, to determine attributions to specific cultural groups, to date various materials, to understand technologies of fabrication, commercial transactions between nations, and power relations, and to confer meaning to all this complex (see *HERITAGE INTERPRETATION*). The chemical identification of the materials used to

make up an object may also explain its deterioration, give clues as to its original appearance, and help establish the best conservation strategies and treatments for it. Recipe books, artists' treatises, pharmacological books, travellers' notes are just some of the primary sources that investigators study in their search for information that may prove useful in understanding the material choices made by an artist. Likewise, modern and contemporary ethnography has studied and recorded the techniques of textile art and painting, which on many occasions can be linked to historical documents or to objects.

The identification of the chemical structures of dyes is complex. The high tinting power of dyes implies that they are found in small quantities and, owing to the dyeing and pigment fabrication methodologies, are usually mixed in complex matrices, either attached to a fiber with the aid of a mordant or combined with binders and other pigments when used for painting. High-performance liquid chromatography (see HIGH PERFORMANCE LIQUID CHROMATOGRAPHY (HPLC)) is still the best alternative for colorant characterization because it separates the different compounds within a sample and identifies them separately. The downside to chromatographic technologies is the need to extract samples from the object to be analyzed (see CHROMATOGRAPHY AND ARCHAEOLOGICAL MATERIALS ANALYSIS). These methods also require the use of reference standards for the proper identification of the compounds. The responsiveness of the new equipments—known as ultra high-performance liquid chromatographers (UHPLC) on account of their enhanced sensitivity—allows the positive detection of fractions of a microgram. As a consequence of the technological developments, sampling has become less damaging than it used to be in previous decades. Chromatographic analyses have also been performed with the aid of photo diode detectors that register the characteristic radiation absorption of colorants at specific wavelengths. HPLCs may be coupled to a mass spectrometer (see MASS SPECTROMETRY (MS)) for the determination of molecular weight that leads to the designation of molecular structures.

Vibrational techniques, such as Raman spectroscopy (see RAMAN SPECTROSCOPY AND MATERIAL ANALYSIS) and Fourier-transformed infrared spectroscopy (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)), have also developed new systems that improve the detection limits of the equipment. Surface-enhanced Raman spectroscopy (SERS) or micro-FTIR are being used more often, giving very positive results in the identification of dyes. Nondestructive and microanalytical techniques can be worked directly over the object without sampling. In the past decade, experimentation with reflectance spectroscopy in the visible and near infrared region has proved to be a useful tool that gives the field good preliminary information at a good speed.

Artifacts are usually integrated into complex mixtures, through superpositions or layers of materials. Their study requires implementation of different analytical techniques and laborious sample preparation. The analytical strategies should be tailored to a clear objective and done by professionals in each of the specialties involved.

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Elemental Analysis of Pottery

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"Demokritos," Greece

History

In comparison to other archaeological materials such as pigments (see CHARACTERIZATION OF PIGMENTS), metals, and glass, the first chemical analyses of archaeological pottery were implemented relatively late—at the end of the nineteenth century (Riederer 1981) (see CHEMISTRY IN ARCHAEOLOGY). The initial scope of the early analyses was the understanding of specific production technologies, such as terra sigillata. During these years, wet chemistry was the only choice of analytical approach for determining the chemical composition, requiring elaborate procedures for the disintegration of the silicates and determination of their components. Nevertheless, first conclusions towards the potential of distinguishing pottery from different production regions based on their elemental composition were drawn, shifting the scope towards provenance. Systematic scientific studies of archaeological ceramics in view of their origin, however, became possible only with the technical development of instrumental analytical methods towards the beginning of the second half of the twentieth century. A series of pioneering studies were implemented, using various methods such as neutron activation analysis (see INAA AND MATERIAL ANALYSIS) (NAA), X-ray fluorescence (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)) (XRF), and optical emission spectroscopy (OES), which eventually can be considered as the starting point of systematic investigation of the elemental composition of archaeological ceramics (Wilson 1978). Since then, elemental analyses of pottery have been subject to substantial developments in analytical techniques and advancements in scientific approaches. While, in the beginning,

the focus of pottery studies was on assessing the principles of elemental analysis and testing the potentials, in the following phase, more and more data were collected, compared, and interpreted in view of specific archaeological questions.

The archaeological scope of elemental pottery analysis remained twofold: to investigate production technology and technology transfer, on the one hand, and dissemination of pottery, on the other. Because occasionally it appeared that elemental analysis by itself could not answer all questions, it was combined in interdisciplinary case studies with alternative methods of pottery examination, such as thin-section petrography (see PETROGRAPHY AND CERAMICS), mineralogical examination, or scanning electron microscopy (SEM). Based on these case studies, an integrated approach to pottery examination developed which essentially improved the data interpretation (Day et al. 1999). Nowadays, elemental analysis of the bulk composition and of surface layers is an integral part of the vast majority of pottery studies, accumulating large amounts of reference data. A relevant technical development during recent years is the feasible application of noninvasive analytical methods such as portable XRF (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)) (pXRF) in cases in which sampling is not possible (Goren, Mommsen, and Klinger 2011). Nevertheless, the laboratory analysis of pottery samples appears to remain important in order to achieve a comprehensive picture of their elemental composition and to build up reference databases.

Bulk composition of pottery

The elemental bulk composition of a ceramic body depends primarily on the elemental compositions of the raw materials that were used for its fabrication. These are basically different types of aluminosilicates containing various accessory minerals. The assumption that raw material sources can be chemically distinguished is the basis for the approach of

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investigating the provenance of pottery based on its elemental composition. The distinctness of raw material sources was formulated in the so-called provenience postulate presuming that “there exist differences in chemical composition between different natural sources that exceed, in some recognizable way, the differences observed within a given source” (Weigand, Harbottle, and Sayre 1977).

It has to be considered, though, that pottery itself is not a raw material. For pottery production, a workable clay paste had to be prepared in order to mold an object, with the additional constraint that this object could withstand the subsequent firing without damage. This required usually some modification of the collected raw materials, such as refinement by grinding, sieving, and elutriation, in order to remove coarse nonplastic components from the clay. It was also quite common to mix different raw materials or to add nonplastic materials as temper in order to control the material properties of the molded object and, more important, of the final product. Therefore, the elemental composition of pottery commonly cannot be linked directly to raw material sources.

The firing of the pottery affected the elemental composition through loss of ignition mainly due to dehydroxylation of the clay paste. With increasing temperature, first the mechanically bound water between clay particles and/or mineral inclusions was removed and later the crystal-bound water, which made the firing process eventually irreversible. Other processes during the firing affecting the bulk composition of the clay are, for example, the loss of molecular carbon dioxide in calcite inclusions and the combustion of organic components. All these processes, however, increased only the absolute concentrations of all other elements, while the ratios of their concentrations remained basically unaffected during firing. Considering the common firing temperatures of archaeological pottery, only a very few elements, such as arsenic and bromine, could be potentially affected by loss due to volatilization.

Consequently, it can be assumed that the *chaîne opératoire* of a specific pottery production, including steps such as raw material selection, clay paste preparation, and the firing process, resulted in a distinct elemental composition

of the final product. This distinct composition is often called the “chemical fingerprint” of a pottery workshop. After all, provenance studies of pottery are indeed based on the provenience postulate including all constraints, such as inner source variability and the nonexistent evidence for its validity.

The elemental composition of the archaeological artifact measured in the laboratory, at last, is not necessarily the same as the original elemental composition of the object. Significant chemical alterations due to use and function of common pottery can be largely excluded, maybe with the exception of technical ceramics used, for example, in pyrotechnical processes. After use, though, the pottery may have been potentially affected by post-depositional alterations. Between use and discarding of the pottery and its discovery, the material was usually exposed to various environmental influences, causing alterations of specific element concentrations by contamination, enrichment, or leaching. Basic examples are rehydroxylation of the fired clay and the formation of secondary calcite enhancing the calcium content. More complex alteration processes can have occurred in extreme environments, such as marine and agricultural contexts. Therefore, the finding context has also to be considered in the integrated elemental analysis of pottery.

Surface composition of pottery

Specific attention should be paid to the elemental composition of the pottery surface. Depending on the surface finishing, the surface composition can be quite different from the bulk composition. Even rather basic techniques such as burnishing and polishing can have had an effect because through the smoothening, commonly by using additional water, the clay paste was refined, reducing nonplastic components such as quartz and carbonates.

In the case that a separate slip was applied, an aqueous slurry had to be prepared. One way to prepare this slurry was the elaborate refining of the clay paste used for the construction of the ceramic body by elutriation. In this way, larger particles were effectively removed, resulting in a proportional enrichment of the clay fraction. In

order to further enhance the vitrification of the slurry during firing, it was sometimes mixed with materials acting as flux, such as potash extracted from plant ash or ash from seaweeds.

Alternatively, the slurry for the slip could have been prepared from different raw materials particularly suitable for slip preparation rather than for body construction. A well-known example is the use of illitic iron-rich clays for the production of Attic black ceramics (Noll, Holm, and Born 1985). But also other types of clay were selected and prepared for slip or paint layers, achieving different colors. These layers, however, did not interact with the actual ceramic body and thus had no effect on the bulk composition of the pottery. This is different in the case of vitreous glazes. Their elemental composition was fundamentally different from the ceramic body and they were additionally mixed with colorants and opacifiers, which potentially could penetrate and contaminate the ceramic body (see GLAZES, SLIPS, AND PAINTS).

Choice of method

In the case of the investigation of archaeological materials, impairment of the studied objects should commonly be restricted to the absolute minimum. Ideally, the analysis should be non-invasive in order to ensure the integrity of the object (see NONDESTRUCTIVE COMPOSITIONAL ANALYSIS OF CERAMICS). In the case of pottery, however, it has to be considered, as already mentioned above, that the elemental composition of the surface is commonly different from the bulk composition. Additionally, in the case of post-depositional alterations and incrustations, these will concern primarily the pottery surface. Therefore, even when using a noninvasive analytical method like pXRF, at least the surface of the pottery should be removed in order to investigate its bulk composition.

Indeed, most analytical methods, used routinely for pottery analysis, implicate sampling of the pottery. In the case of pottery fragments or shards, this is usually acceptable and the samples can be used also for other methods in view of integrated examination. The necessary sample amounts vary from several milligrams, as in the case of inductively coupled plasma spectrometry

mass spectrometry (see ICP-MS AND MATERIAL ANALYSIS) (ICP-MS), up to several grams, as in the case of wavelength-dispersive X-ray fluorescence (WDXRF), optical emission spectroscopy (OES), and atomic absorption spectroscopy (AAS). Even though the sample amount should be kept at a minimum, it should be large enough to represent sufficiently the material. The suitable amount depends essentially on the type of pottery in view of its homogeneity and coarseness. Commonly, pottery samples are taken by clipping and subsequent powdering or by drilling. Alternatively, small samples can be taken and immediately analyzed by laser ablation, as in the case of laser ablation inductively coupled plasma mass spectrometry (LA-ICPMS) and laser-induced breakdown spectroscopy (see LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS)) (LIBS). For other analytical methods, a more or less elaborate sample preparation is necessary, potentially involving silicate dissolution or fusion of the sample powders. Sufficient avoidance of contamination during sampling and sample preparation is self-evident.

Among the various methods that can be used for elemental analysis of pottery there exist substantial differences in terms of the elements, the concentrations of which are feasible to determine, and in terms of detection limits and precision. Each method provides actually only a limited selection of element concentrations. Some methods, such as XRF, OES, and AAS, are rather suited to analyzing major and minor elements, while others, such as NAA and ICP-MS, are adapted to trace element analysis. The choice of a suitable method depends on the questions to be solved in the analytical study. In the case of provenance studies, for example, a sufficient number of trace element concentrations measured with high precision is necessary to distinguish pottery produced from different clay pastes, while major element compositions provide rather more information about clay paste preparation and preferences for specific types of raw materials.

Another issue to be considered in the choice of a suitable analytical method is the potential for comparing new data with existing reference data. Even though comparison of element concentrations determined with different methods is basically possible, practical experience has indicated that comparison of data determined with the

same or a similar method is more straightforward. It should be taken into account that apart from the precision, which is the reproducibility of the applied method, also the accuracy, which is the closeness to the true value, is relevant for comparing individual element concentrations. Therefore, it may be necessary to estimate calibration factors for interlaboratory comparisons.

In certain case studies, the spatial distribution of the elemental composition can be the object of investigation, for example when slip or paint layers are explored. In this case, the analysis can be combined with microscopic examination. A common approach is SEM of pottery sections in combination with energy-dispersive spectroscopy (SEM-EDS) or electron microprobe (EMP). Alternatively, laser ablation can be used for ICP-MS or X-ray spectroscopy at microscale, using μ XRF (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)) or particle-induced X-ray emission (see ION BEAM ANALYSIS (PIXE/RBS)) (PIXE).

Variation of the elemental composition

Most of the interpretation of the analytical results is based on the evaluation of similarity or dissimilarity of elemental compositions. Similar bulk compositions are expected to indicate common origin of production, while dissimilar bulk compositions indicate different origin. Looking, on the other hand, at the surface layers, specific differences of the surface composition compared with the bulk composition indicate particular surface treatments. The reference pattern of a pottery production site, however, is actually not a “chemical fingerprint,” which would refer to a singular elemental composition. In fact, the determined elemental composition always implicates variation. The starting point was the natural geochemical variation within the selected raw material sources, which is already described in the “provenience postulate.” The clay paste processing introduced further variation, because the craftspeople were interested in the preparation of a workable clay paste rather than complying with specific recipes and exact amounts of components. The elemental composition, measured with the analytical method of choice, eventually introduces analytical uncertainties, additionally

interfering with the compositional variation of the pottery.

Therefore, in the case where an elemental reference pattern of a specific production site is investigated, it appears commonly to be necessary to analyze multiple pottery samples from the site in order to define the average element concentrations and to estimate their variation. Elemental analysis should always start with a well-considered sampling strategy. The similarity or dissimilarity of two element compositions can only be assessed under consideration of their variations. The compositional variation finally affects the level up to which pottery production of different origin can be distinguished. If the natural variation of the raw materials commonly used for pottery production was small throughout a specific region and extensive clay paste processing was not necessary, it can be difficult to distinguish different production sites within the region. In other cases, it can be possible to distinguish even individual pottery workshops at the same production site. In any case, the analytical method has to be suitably selected in order not to obscure potential compositional differences by introducing unnecessarily large analytical variation.

Statistical treatment of elemental compositions

In order to explore similarity or dissimilarity of elemental compositions, the analytical data have to be evaluated using suitable statistical approaches. Certain constraints have to be considered due to the nature of pottery compositions. The variation of a specific element concentration within a series of pottery samples, for example, can be estimated by determining the standard deviation of the measured values, presuming, though, a normal distribution of concentration values. In the case of the natural variation of trace elements, however, their concentrations are expected to follow rather a log-normal distribution. Furthermore, element concentrations in pottery are not completely independent of each other. Particular elements are correlated because they are associated with the same mineral components, which can vary in the original clay

paste or be affected by post-depositional alteration. Finally, a general enrichment or depletion of trace elements can be related to the addition of varying amounts of temper materials, which are poor in trace elements, or to variation of the firing conditions and the correlated loss of ignition.

The assumed natural log-normal distribution of element concentrations can be accounted for by using logarithmically transformed data. This has the additional advantage of a basic normalization of the data, which appears to be necessary because the absolute concentrations of the individual elements range over levels from sub-parts per million (ppm) to weight percent. In order to consider correlations, ratios of element concentrations can be evaluated instead of absolute concentrations. In the variation matrix, defined by Aitchison (1986), logarithmized ratios of all element concentrations are evaluated, providing the “total variation” as a measure for the compositional variation of the studied assemblage. Log-ratio transformed data can be used for further exploration of the dataset with multivariate statistical methods such as hierarchical cluster analysis (see CLUSTER ANALYSIS) or principal component analysis (see PRINCIPAL COMPONENT ANALYSIS) (PCA).

An alternative approach for considering element correlations is the use of the Mahalanobis distance for determining probabilities of the similarity or dissimilarity of compositional groups (Bieber et al. 1976). This distance is based on the covariance matrix of the element concentrations of a group of samples, which are presenting assumedly the same elemental composition. The data are normalized by their variations. Individual samples can be compared with a compositional group and in the case of similarity they can be incorporated. In order to adjust the above-discussed general enrichment or depletion of trace elements, an additional best relative fit can be introduced.

SEE ALSO: Characterization of Ceramics; Pottery Data Quantification

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Embalming

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Throughout history, practices to preserve the human body after death, and thus to stabilize it against degradation by impeding enzymatic and microbotic activity, and sometimes also to restore its antemortem appearance, are a cross-cultural phenomenon (Lynnerup 2007; Papageorgopoulou et al. 2009). Religious beliefs, especially those that link the achievement of eternal life to the intactness of the body, are the earliest motive for which corpses were artificially embalmed. These beliefs were surely supported by the observation that bodies did not decompose under certain conditions in which partial or complete natural preservation occurred, such as freezing, desiccation by dry heat, exsiccation by dry cold, or under specific soil conditions. Only much later, the rising interest in human anatomy led to the development of techniques for the preparation and preservation of anatomical specimens and, consequently, to a progressing separation of embalming practices carried out in a funerary context and those performed for scientific or diagnostic purposes (Brenner 2014). Generally, the history of embalming is divided into three main periods: (1) ancient societies including those of ancient Egypt and Nubia, the Guanches, South America (the Chinchorro people being the earliest who performed artificial mummifications), and Asia; (2) medieval Europe and the Renaissance, often known as the “anatomist’s period of embalming,” characterized by an increasing demand for cadaver studies as a consequence of scientific developments, particularly in medicine; and (3) the modern era, starting in the nineteenth century with development of reliable methods to inject various chemical preservation agents, nowadays mainly formaldehyde, into the arterial system (Brenner 2014).

With the advance of tissue fixation and histopathological examination techniques for diagnostic objectives, paleopathological investigation of ancient embalmed specimens has evolved further. Besides invasive examination methods, such as histological analysis, analysis by gas chromatography and mass spectrometry, and ancient DNA analysis, noninvasive examination by various imaging techniques based on computed tomography (CT), magnetic resonance imaging (MRI), and recently terahertz (THz) imaging has been applied in several interdisciplinary research projects (Ruhli, Chhem, and Boni 2004; Lynnerup 2007; Papageorgopoulou et al. 2009; Giuffra et al. 2011).

Ancient societies

The Chinchorro populations were sedentary hunter-gatherers who inhabited the arid Pacific coastal regions of the Atacama Desert in present-day Chile and Peru from approximately 7000 to 1500 BCE. They belong to the earliest societies that performed artificial mummification. The oldest artificial mummy, a children’s mummy from the Valle de Camarones, could be dated to about 5000 BCE. In the following 3,500 years, various styles of mummification evolved, until the practice of mummification among the Chinchorro came to a halt around 1500 BCE. The Chinchorro mummies vary greatly in the degree of complexity and sophistication of the applied mummification techniques, which can be differentiated into black mummies, red mummies, mummies with bandages, mummies with mud patina, and naturally mummified bodies.

The different artificial mummification practices involved various intentional alterations of the cadaver, such as skinning, defleshing, evisceration, and excerebration, followed by often elaborate layered remodeling using organic and inorganic materials, depending on the extent to which the body was initially dismantled. The natural mummification process, on the other hand, essentially consisted of letting the corpse

desiccate in the salinity and dryness of the Atacama Desert. The varying practices most likely correspond to cultural changes over time rather than social hierarchy or different coexisting cultural groups. However, since the Chinchorro populations buried their dead with very few cultural offerings, a certain type of mummification cannot be correlated to a specific material culture. Findings also indicate that many of the recovered mummies, especially black- and red-style mummies, have at the time been repaired, possibly because they were used in the context of religious rituals before eventually being buried in family groups (Arriaza and Standen 2002).

The mummies of ancient Egypt are probably the supreme exemplification of procedures applied against the natural process of putrefaction and therefore disfiguration and eventual loss of the dead body. As early as the First Dynasty (approximately 3150–2890 BCE), specialized members of the priest caste were responsible for embalming and mummification. While the motives for artificial embalming traditions were of religious nature, the actual embalming techniques are likely to have originated from an imitation of the natural dehydration process of ancient burials in the desert. As the proto-archaeologist Anne-Claude-Philippe, Count of Caylus (1692–1765), stated in 1749: “It appears that the Egyptians owe the idea of their mummies to the bodies they discovered dried in the burning sands of a region in Egypt, which, carried away by the winds, bury travelers and preserve their bodies, consuming fats and flesh, without altering the skin” (Gannal 1841).

Over the centuries, the embalmers of ancient Egypt introduced three fundamental steps for their sophisticated mummification procedures: evisceration (and excerebration) of the body, desiccation in natron, and anointment with natural compounds, with polymerization of unsaturated oils and fats contained in these anointments being the main principle of tissue fixation. Their exact composition, however, remains uncertain, due to the absence of primary textual evidence. Based on the only available secondary literature by Herodotus (484–430 BCE), Diodorus Siculus (first half of the first century BCE), Strabo (approximately 63 BCE–23 CE), and Pliny the Elder (23–79 CE), the use of beeswax, plant oils and plant resins, animal fats, various aromatics,

and even petroleum bitumen can be presumed. A few published studies have confirmed some of these assumptions by gas chromatography and mass spectrometry, with results greatly varying over different time periods and locations (Buckley, Clark, and Evershed 2004; Papageorgopoulou et al. 2009).

The Guanches on the Canary Islands also practiced mummification techniques based on evisceration and drying of the corpse. The majority of these mummies were produced prior to Spanish colonization of the Canaries during the fifteenth century. Here the cadaver was eviscerated through an abdominal or lateral incision, washed with salt-water, and eventually filled with resins and aromatic oils. Another less expensive method was to inject a highly corrosive liquid into the abdomen, so that the dissolved and liquefied viscera could be swept out. The bodies treated in this fashion were then dried in the sun or smoked for 50 days. Finally the bodies were coated with ointments and resins, then wrapped in goatskins, and eventually placed in tree trunks or deposited in funeral caves.

Another ancient preservation method was the immersion in honey. Publius Papinius Statius (40–96 CE) reports on the Greek emperor Alexander the Great (356–323 BCE) being subjected to such treatment after his death, so that his remains could be transported from Babylon to Alexandria. However, it is unknown whether Herophilus of Chalcedon (approximately 330–255 BCE) and Erasistratus of Ceos (approximately 304–250 BCE), who only a few decades later conducted anatomical studies in Alexandria, also used this method (Longrigg 1988; Brenner 2014).

In China, extraordinarily well-preserved artificially embalmed human remains have been found in the tombs of Xin Zhui and Mawangdui Han, which date back to the Han dynasty (206 BCE–220 CE). However, little is known of the embalming agents and procedures that were applied (Bonn-Muller 2009).

The knowledge and practice of artificial embalming had spread to Europe from the ancient societies by about 500 CE, with evisceration therefore still characterizing the principal measure to prevent the cadavers’ decay (Giuffra et al. 2011). Only a few earlier cases have been reported from the time of the Roman Empire, such as a partly mummified body, found in

northern Greece, which was dated to 300 CE. A chemical analysis identified compounds of coniferous and pistachio resins, myrrh, and other spices (Papageorgopoulou et al. 2009).

The anatomist's period

The “anatomist's period of embalming” ranges from early medieval Europe through the Renaissance with the growing impact of scientific developments in medicine and a consecutive demand for anatomical cadaver studies. Medieval embalming practices included evisceration, soaking the body in alcohol or vinegar, insertion of salts and aromatic herbs into the body cavities and previously incised soft tissues, and finally wrapping the body in tarred or waxed sheets (Brenner 2014). The contemporary physicians Peter Forestus (1522–97) and Ambroise Paré (1510–90) were among the earliest to document such methods. Leonardo da Vinci (1452–1519) also described methods used to preserve the cadavers he studied. His embalming fluids contained turpentine, camphor, oil of lavender, vermilion, vine, rosin, sodium nitrate, and potassium nitrate. Other prominent anatomists and physicians like Bartholomeo Eustachi (1520–74), Reinier de Graaf (1641–73), and Jan Swammerdam (1637–80) have reported similar procedures. By the seventeenth century, the practice of embalming corpses in Europe had become widespread and canonical (Giuffra et al. 2011). A representative description is the brief orientation “*la façon d'embaumer les corps morts*” in “*La Grande Chirurgie des Tumeurs*” (Lione 1657) by the physician Jean Vigier (1600–59).

“All the bowels and viscera must first be discarded, except for the heart, which must be washed with brandy and sprinkled with saline powders, and then placed in a lead box, and given to the parents or friends of the deceased. The entrails and the marrow of the brain will be removed after having opened the (body) parts, and they will be buried. Along the arms, shoulders, the back, the buttocks, thighs, legs, and particularly, at the location of the great veins and arteries, incisions will be made to let out the blood and humors or moisture, which would (otherwise) putrefy. After the incisions have been made, the whole body should be washed with

sponges imbued with brandy and strong vinegar After the incisions, the internal cavities, and the whole body have been thoroughly washed, it is necessary to carefully wipe all the said parts with tow, sponges, or cloth, and then to fill the said incisions and cavities with a powder containing the following: absinthe, marjoram, sage, route, lesser knapweed, mint, laurel, rosemary, lavender, pennyroyal, coloquintide, aloe, common salt and potassium alum. The incisions and cavities being stuffed with the said powder shall be sewn, and the whole body also anointed After the body has been anointed, it will be covered with the said powders, then wrapped in a shroud, and finally in a well waxed cloth, and, sewn in it will be placed in a leaden coffin, filled with sage, mint, heather, marjoram, absinthe, rosemary, red roses, cloves and other dry aromatics. If the dead man is poor, he will be washed with salt water, vinegar, or with lye of oak, fig and grapevine, in which these herbs will be boiled, then he will be wiped with sifted ashes, and the incisions, once dry and clean, together with the cavities will be stuffed with common salt”

Before the introduction of modern chemical preservatives like carbolic acid, phenol, or later formaldehyde, the preserving agents predominantly used in the anatomies were thus alcoholic solutions of arsenic or alumina salts.

Vascular injection of these substances is only rarely reported, however, before the mid-eighteenth century. Frederik Ruysch (1638–1731) is thought to have embalmed by injecting a mixture of pig's blood and the chemical preservatives Berlin blue and mercury oxide into the vascular system (Driessen-Van het Reve 2006). A well-documented procedure, developed by Jean Nicolas Gannal (1721–83), was based on injection of aluminum sulfate or aluminum chloride into the vascular system, in addition to the at the time still customary practice of incision, evisceration, and disinfecting surface treatment. However, it provided satisfactory preservation only for a limited period of time (Gannal 1841). The embalming procedure of Italian anatomist Guiseppe Tranchina (1797–1837) is probably the earliest one documented to involve arterial injection of arsenic solutions without previous evisceration of the body. Among British physicians and anatomists to practice embalming by

arterial injection of different solvents (mainly turpentine) and essential oils (chamomile and lavender) were William Hunter (1718–83) and his brother John Hunter (1728–93) and Matthew Baillie (1761–1823) (Brenner 2014).

Modern tissue preservation techniques

In the course of the nineteenth century, French, Italian, and British scientists refined their injection techniques, permitting the preserving fluids to infiltrate every part of the cadaver. With the advance of embalming by arterial injection, research for new preserving agents directed the anatomist's interests to the field of chemistry. Also starting in the mid-nineteenth century, the embalming procedures begin to separate into those performed as part of mortuary practice and those for diagnostic and scientific purposes, with different aims in terms of presentation and long-term preservation. In the New World, the American Civil War led to a drastic increase in funerary embalming practices, as a result of members of the military dying far from home and the necessity to bring their remains back for local burial. The prevention of the spreading of disease was a further motive behind funerary embalming at that time. Phenol, after its discovery by chemist Friedlieb Ferdinand Runge (1794–1867) in 1834 and its later introduction as a surgical antiseptic (5% aqueous solution of phenol) by Sir Joseph Lister (1827–1912) in 1865, became widely appreciated for its bactericide effects and was introduced to anatomical embalming by Sigismund Laskowski (1841–1928) in 1886. Alternatively, 8-hydroxyquinoline (Chinosol), which at that time was also used to treat diarrhea, was used in the same manner by anatomist Paul Schiefferdecker (1849–1931). The discovery of formaldehyde by the German chemist August Wilhelm von Hofmann (1818–92) in 1869 and the discovery of its tissue-fixating properties by Ferdinand Blum (1865–1959) in 1893 essentially mark the beginning of modern embalming. Within a few years, numerous medical schools throughout Europe introduced formaldehyde to preserve biological and anatomical specimens. Its unfavorable effects, such as irritations of the skin and the respiratory system, conjunctivitis,

and headache, were already known at the time. Nowadays, neutral buffered formalin (NBF), equivalent to 4 percent paraformaldehyde in a buffered solution plus a preservative (methanol), preventing formaldehyde from converting to formic acid, is most widely used to preserve biological tissues. However, fixation techniques have also been developed for more specific clinical and diagnostic applications, such as the method introduced in 1992 by the Austrian anatomist Walter Thiel (1919–2012), which uses a mixture of boric acid, ethylene glycol, ammonium and potassium nitrate, chlorocresol, sodium sulfate, and formaldehyde. It provides excellent color preservation and preserves the soft tissues' flexibility, making it very valuable for surgical training (Thiel 1992). Another fairly recent development is the preservation method developed by Gunther Von Hagens in 1978, and it is currently used in both teaching and research. His so-called plastination method consists of a slow replacement of tissue fluids and partly also tissue lipids by polymers under vacuum, resulting in clean, dry, odorless, and very durable biological specimens. Remarkably plastination leaves the radiographic density of tissues unchanged.

In daily clinical practice, cryopreservation and embedding in paraffin are the two most widely used ways to preserve human tissues, especially for histological analysis, where the preparation of thin sections, which are mounted on glass slides and stained to demonstrate normal and abnormal structures, is to this day essential for microscopic analysis.

The use of human tissue and human remains presents per se an ethical dilemma. In the course of history, anatomists, physicians, and even archaeologists often engaged in activities, even if considered immoral by the public. Today, embalming and preservation of human tissues and whole bodies is needed and widely used for diagnostic, medico-legal, scholastic, scientific, and funerary purposes. In all of these fields, specific ethical and sanitary aspects have to be respected and existing guidelines must be obeyed. In 2014, for instance, the International Federation of Associations of Anatomists (IFAA) established good practice recommendations regarding the donation of human bodies and tissues for anatomical examination. While such guidelines and public awareness are widely

established for modern human remains, analogous codes of conduct must be employed for ancient human remains as well. This ethical debate should consider various aspects such as informed consent but also the degree of intrusion or destruction in relation to an expected scientific outcome.

SEE ALSO: Bodies and Embodiment; Chemistry in Archaeology; Conservation Science; Gas Chromatography–Mass Spectrometry (GC-MS); Imaging in Human Remains; Paleopathology

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Fibers

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Fibers are the components of yarns and textiles. They are recognized by their long, fine shape and are typically found in combinations of some sort; individual fibers are barely visible to the naked eye. Their chemical composition and molecular arrangement give them unique properties of flexibility, strength, and resilience.

Prior to the twentieth century, humans used a wide range of naturally occurring fibrous materials. There are three groups of natural fibers that are classified on the basis of their chemical composition: cellulose (from plants), protein (from animals), and mineral (asbestos).

Cellulose, the building material for plant cell walls, is a linear polymer. Cellulosic fibers grow in plant stems, inner tree bark, leaves, and seed hairs. The oldest fibers and their dependent technologies relied on long fibers found in the stems, inner bark, and leaves of plants. Plant sources vary by region. Some examples are flax (*Linum*), hemp (*Cannabis*), ramie (*Boehmeria*), linden (*Tilia*), cedar (*Cedrus*), paper mulberry (*Broussonetia*), abaca or banana (*Musa*), sisal, and henequen (*Agave*). Flax, domesticated about 10,500–9,000 years BP and used for seed oil as well as for fibers, was one of the agricultural founder crops in the Levant (Weiss and Zohary 2011). The short seed hair fibers of cotton (*Gossypium*) came into use more recently, with independent domestication (see DOMESTICATION) events in the eastern and western hemispheres.

Protein fibers include keratins in the form of mammalian hair or wool and avian feathers, as well as fibroin filaments or silk made by moths in the domesticated *Bombyx* and wild *Antheraea* genera. Humans have gathered tufts of fibers from the landscape during annual molts, or have

plucked, combed, and shorn them from animals such as sheep, goats (see SHEEP AND GOATS), and camelids (see LLAMAS AND ALPACAS). Animal domestication (see DOMESTICATION) led to an improvement in fiber properties, for instance the development of finer wool fibers in sheep (*Ovis aries*). Wool appears in the archaeological record around 5,000 BP, long after the domestication of hairy, wild sheep.

Fibers of asbestos suitable for spinning and weaving break away from chrysotile mineral formations. Accounts from the Mediterranean basin and China describe it as a lustrous and fireproof novelty more than 2,000 years ago (Cameron 2000).

Human-made fibers were developed in the latter half of the nineteenth century, beginning with the regeneration of natural cellulose. In the process, wood pulp or another cellulose source is chemically altered in order to dissolve the polymer and extrude it into long, lustrous, cellulose filaments. Twentieth-century chemists invented synthetic polymers using petrochemicals as a starting point; human-made fibers exceeded 50 percent of the world's total fiber production per annum by the end of the twentieth century.

Small fragments of fibrous materials in the archaeological record offer a window into the minds, landscapes, and seasons of past peoples. The acquisition of specific fiber resources, whether gathered, cultivated, or herded, reveals human relationships with fiber sources and suggests an annual schedule of activities. Evidence of higher fiber technologies such as fiber improvement, dyeing, spinning, and textile formation points to the maker's process, the intended end use of an object, and a cultural accumulation of specialized knowledge. Patterns of fiber use give insight into past ways of life, economic relationships, and group identity.

Identification and analysis

Optical microscopy (see OPTICAL MICROSCOPY) (OM) is the principal tool used in fiber examination.

Brightfield and polarized light techniques provide multiple pieces of information from the examination of a single fiber that cumulatively contribute to fiber identification and classification and to the characterization of fiber condition. With OM, observers can see surface morphology and internal morphology as well as evidence for molecular arrangement.

Scanning electron microscopy (see SCANNING ELECTRON MICROSCOPY) (SEM) shows the distinctive surface morphologies by which some natural fibers can be identified. Energy-dispersive analysis of X-rays (EDS) is often combined with SEM to offer complementary information on elemental composition (see SEM-EDS AND MATERIAL ANALYSIS). For example, SEM displays the characteristic morphologies of siliceous and calcareous inclusions in plant cells called phytoliths, while EDS provides evidence for the presence of silicon and calcium (see PHYTOLITH ANALYSIS). Spectrometric methods such as UV-visible, infrared (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)), and Raman spectroscopy (see RAMAN SPECTROSCOPY IN CONSERVATION) provide information on chemical composition, while combinations of chromatographic techniques (see CHROMATOGRAPHY AND ARCHAEOLOGICAL MATERIALS ANALYSIS) with spectroscopy have been used to identify fibers as well as their colorants (see DYES).

Fibers can be dated through accelerator mass spectroscopy (AMS) radiocarbon analysis (see DATING IN ARCHAEOLOGY). New sample preparation methods use very small amounts of material, and the sequencing of methods provides information from a single sample. For example, direct analysis in real time-mass spectroscopy yields compositional data; subsequent AMS analysis of the carbon of the same sample yields a radiocarbon date. Isotopic ratios of elements other than carbon supply additional information: keratin, the protein in animal hair fibers, retains strontium isotopes in ratios that are consistent with the strontium isotope ratio in the environment where the protein grew into hair.

Preservation of evidence

Perishable fibrous materials survive in particular archaeological contexts. Desert and arid cave or rock shelter environments desiccate fibrous organic materials. In the extreme cold of ice and permafrost, they are preserved through freezing. Anaerobic conditions, as found in cold lakes, inhibit microbial degradation. Proteinaceous materials are durable in acidic bog conditions, while celluloses survive in alkaline conditions. Organic fibers persist in otherwise inhospitable burial environments when they are associated with mineral ions that retard microbial activity. Occasionally these ions permeate and replace the fiber structure, yielding pseudomorphs, which retain the shapes of the original item but differ in composition. Fibers that have been charred prior to burial resist microbial degradation and can survive the archaeological context.

SEE ALSO: Conservation of Fibrous Materials; Textiles

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Gemstones

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In the current definition of gemstones we can include a wide range of “gemological materials” or “gems,” precious or semiprecious stones where natural or faceted and polished fragments of a large group of minerals belonging to different classes and compositions and some mixtures of minerals such as lapislazuli are included (Arem 1977), but also some natural materials of animal, plant, or meteoritic origin like amber, jet, or tektites—moldavite—(Rapp 2009), which have been used by humans for ornamentation and personal adornment.

In the classification of gemstones, since for the most part they come from natural minerals, we can see that virtually in all mineral classes of Dana’s classification, modified later during the twentieth century by Strunz and others, some minerals with gemological interest are present. However, the majority of gemological materials belong to the group of silicates, specifically the crystalline and microcrystalline varieties of quartz, opals, and other groups of silicates. Other minerals classed as oxides, phosphates, and carbonates also include some examples of the most important gems used within history.

It is considered that the characteristics that give the gems their special attraction are essentially threefold:

- Beauty, a concept certainly subjective and subject to the whims of fashion, but with objective components, such as color, the geometric crystalline form, shine, transparency, light dispersion, and other optical properties.
- Durability or ability to resist without substantial damage shock and friction with other materials. Thus, the admiration that the ancient felt for the diamond was due not to its brightness, which was only discovered in

achieving its cutting and polishing, but to its great hardness.

- Finally, its scarcity or rarity is valued in a gem, which gives to its owner a sense of power, prestige, and individuality.

Since ancient times, there seems to be a human tendency, manifested in all societies and cultures in which men and women tend to use for personal adornment the most striking, or rarest objects that nature places at their disposal. Although gems are generally high-hardness materials in some cases, gemological mineral materials or substances of medium or low hardness (turquoise, variscite, amber) have been used no doubt because of other properties such as luster, color, aesthetic value, or rarity. From ethnographic studies on populations with lifestyles that have remained since ancient times, this fact may be related to personal vanity, but also very directly with the testimonies of social status, power, or uniqueness of whom carries the valuable object or their supposed magical or supernatural powers.

We know according to archaeological findings that humans have used, recognized, and could carve up to 15 different kinds of “gems,” among which there are many materials of organic origin such as bone-ivory, various shells, coral, amber, jet, and some natural glasses. Since the Paleolithic, some types of minerals or substances certainly have been used as an element of personal or symbolic ornaments. So, amber fragments have appeared in caves with Paleolithic occupation in northern Spain, figurines made in mammoth fossil ivory in Germany (40,000 BC), quartz rock crystals in European Paleolithic sites, and so on.

The presence in the archaeological record of some of these materials in sites far away from their place of geological origin allows us to establish the existence of mobility and routes or distribution pathways, at least since Neolithic times (Querré et al. 2014).

If we make a historical development of the use of the different gemological materials by human societies and their geographical distribution, we will observe major differences and some

similarities in terms of the mineral species or type of substance used. These differences are due to the geological origin of the gemstones themselves, cultural preferences for one or more substances and the historical period that we consider.

To summarize, we can cite some examples relating to the main gemological materials and their use throughout the history of human societies, that we can study through different techniques of archaeometry (Rapp 2009; Edwards and Vandenabeele 2012; Vandenabeele and Donais 2016).

In this respect, we can find examples of gemological minerals utilized almost without interruption from ancient times to the present, and with a wide geographical distribution, almost worldwide. The mineralogical classification of Strunz has been followed (Strunz and Nickel 2001).

Native elements, such as diamond, have been used as gems since ancient times, with increased use after it began to be polished, faceted, and its high brightness observed. The first examples of exploitation appear to be in India, where, in Roman times a true distribution route to the Mediterranean was worked.

Sulphides. Pyrite and sphalerite. Pyrite has had some gemological applications, as occurs in the skulls-mosaic of Aztec times, in Mesoamerica, with turquoise.

Oxides. The main gemstones of this group are aluminum oxides such as corundum (ruby and sapphire), with a large presence in South-east Asia (Burma, Sri Lanka, India, Thailand, etc.) and a wide temporal distribution to long history (Calligaro et al. 1999). Another important mineral is hematite, typical in the Mesopotamian cylindrical seal manufacture. Spinel, rutile, cassiterite, and chrysoberyl are less abundant in the archaeological register (Rapp 2009).

Halides as fluorite, a mineral with a scarce use as gemstone. Some examples of its use especially appear in Roman times, for the manufacture of luxury jars distributed in Europe that, according to Pliny, came from Persia.

Carbonates as calcite, smithsonite, rhodochrosite, aragonite, malachite, and azurite. Calcite and aragonite appear especially in small necklace beads from the Neolithic in Europe, Asia,

Africa, and so forth, but many significant examples of Paleolithic objects such as the Venus of Tursac, France, from the Gravettian period (25,000 BC) can be cited. Malachite necklace beads and pendants have been found in native societies of South America, Africa, and Europe; also in large vessels manufactured in the nineteenth century in the Russian Urals (Bukanov 2006).

Sulphates. Gypsum (alabaster), with a very limited use as a gem because of its low hardness, but present in different prestige objects such as second-first millennium BC cups of the New Kingdom, Egypt (Rapp 2009).

Phosphates. Apatite, amblygonite, lazulite, wavelite, and variscite-turquoise. This group of minerals has great interest to societies through time. It is to emphasize the use of variscite throughout the European Atlantic southwest during the Neolithic and Chalcolithic, between 5000 BC and 3000 BC, especially associated with the Atlantic megalithic phenomenon, with ancient mining activity in three areas of Spain and distribution throughout the Iberian Peninsula and France (Querré et al. 2014; Domínguez-Bella 2012). Another phosphate used worldwide as prestige material has been turquoise, blue-green in color, with different geological deposits in the world and in use as gemological material from ancient times to the present. Turquoise objects are remarkable in Mesoamerica (e.g., Aztec) (Cruz-Ocampo et al. 2007) and western North America with highly developed distribution networks over thousands of kilometers (widely used in ancient Egypt, with mining in Sinai and Iran, China, Tibet, etc.).

Lazulite and associated minerals such as calcite and pyrite form the known lapis lazuli, an exploited gem in Afghanistan since ancient times and distributed throughout Asia to the Mediterranean, especially in Mesopotamia and Predynastic Egypt. Very abundant in archaeological records, from China and the Himalayas to the Mediterranean East. The second largest deposit of lapis lazuli, in northern Chile, also used as a gem in pre-Hispanic times by the populations of the Diaguita culture. Other smaller deposits also exist in Burma, Italy, and the former USSR (Bukanov 2006).

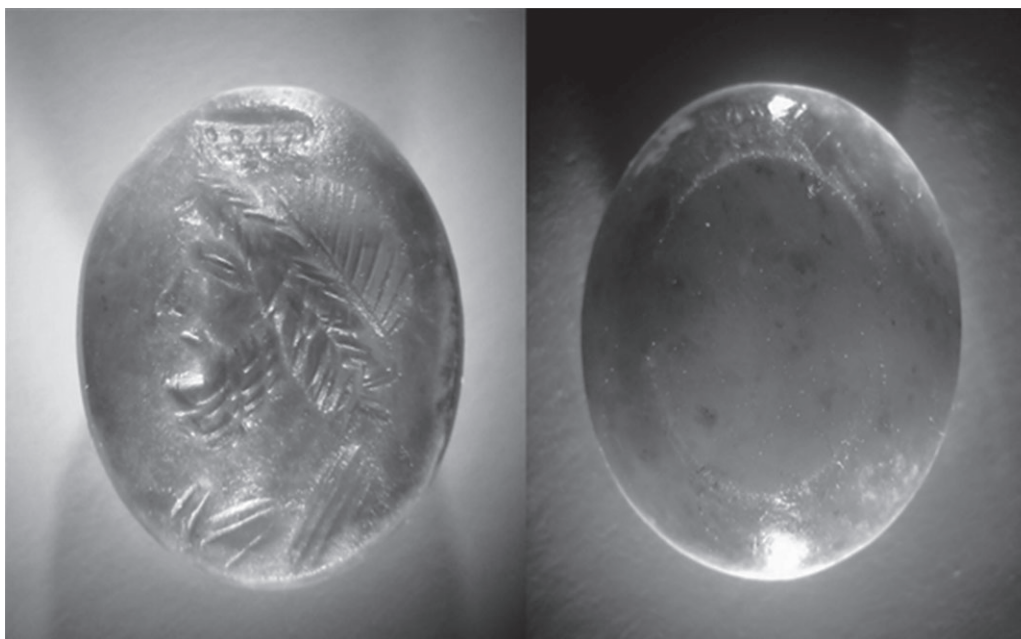


Figure 1 Roman intaglio in chrysoprase or *chrysoprasus*. First century AD, Puerto Real, Cádiz province, Spain. Private collection. Photo: S. Domínguez-Bella. (1.07 × 0.83 × 0.53 cm).

Nesosilicates such as olivine, garnets, zircon, andalusite, sillimanite, topaz, staurolite, and sphene. Within this group, olivine or peridot is an important gemological mineral, especially in ancient Egypt, present in Pharaoh Tutankhamen's jewels' that has been mined from as early as 1500 BC and exploited, for example, in its main geological source in the ancient world, the Topazos Island, now known as Zabargad (St. John's Island) in the Egyptian Red Sea, cited by Pliny the Elder in his *Natural History* (23–79 AD) (Lucas and Harris 1989). Also a nesosilicate, and perhaps the most widely used as a gemstone is the garnet, in different varieties, especially red in color widely used in Roman times and as a highly valued gem in the Visigoth-Ostrogoth culture in Europe.

Sillimanite is an important material in the Neolithic and Chalcolithic of the Iberian Peninsula and the Atlantic facade of Europe, for the manufacture of axes and adzes of very different sizes and in some cases, with a nonfunctional use. Its presence together with jadeite in the grave goods of the great megalithic tombs in Brittany confirm this

high symbolic or prestige value. Andalusite (var. chiastolite) is a mineral that because of its peculiar form in crosses has been of symbolic or magical value as a gemstone in northern Spain, from Celtic times to the Middle Ages, and in the Southern Cross Stone in the Araucanian Indians societies of the Patagonia.

Cyclosilicates. In this mineral group, perhaps emeralds and aquamarines are the most appreciated and used gems among history. Within the green stones group and along with other varieties of beryl, the emerald, for its natural geometric shape, brightness, hardness, and color, has aroused a special interest throughout history. It appears in jewelry of ancient Egypt and then in Rome, after the Ptolemaic era, with a wide circulation in the empire from the three known deposits at the time, the mines of Cleopatra in Egypt, Pakistan, and the Austrian Alps. Also in Colombia (Rapp 2009).

Inosilicates. Pyroxene, rhodonite, amphibole. The most remarkable substance of this group is known as jade, formed by jadeite and nephrite minerals, with its main geological outcrops in Central Asia, Guatemala, and the Italian

Alps. In Asia, it was greatly appreciated in the Chinese and Korean cultures, with a use that continues until today, aristocratic tombs of the Han Dynasty (206–220 BC) present numerous and refined objects. Alpine jade, mined in Neolithic times for the manufacture of polished axes that are exported through thousands of kilometers as elements of prestige to great parts of Europe, appearing in numerous megalithic tombs, especially on the Atlantic facade, North Italy, France, central Europe, and so on. Another important area for this mineral is Mesoamerica especially associated with the Olmec, Mayan, and Aztec societies in Mexico and Guatemala, with the main deposits in the Motagua Valley (Guatemala) (Cruz-Ocampo et al. 2007).

Phyllosilicates. Talc (steatite) and serpentine are the two substances of this group with the greatest usage since ancient times. Talc is used in Europe since the Paleolithic times in the elaboration of pendants and small statuettes such as the “Venus of Grimaldi” a green steatite figurine from Balzi Rossi caves, Liguria, Italy. Serpentine records appear in many Neolithic sites of western Europe, also in the Inuk culture of north Canada or in Africa (Zimbabwe).

Tectosilicates. Quartz, opal, xilopale, feldspars, feldspatoids, scapolites. In this group, we can note crystalline, microcrystalline, and amorphous varieties of silica, with wide distribution in time and in many geographical areas (Figure 1). In its crystalline varieties such as rock crystal, amethyst, prase or smoked, the natural crystalline form, generally prismatic, is present in Paleolithic and Neolithic archaeological finds in Europe and North Africa (Domínguez-Bella 2012); and in Protohistory (examples in the Mycenaean culture, and Dynastic era in Egypt) or in Roman times throughout the whole empire, where finely crafted examples appear. In Mesoamerica, spectacular examples of carved quartz skulls are found.

In these latter areas, apart from jewelry, engraved gems and hardstone carvings as in the Indus Valley from the seventh millennium BC vases, bowls, and cups (“*myrrhina vasa*” in Roman times), were highly appreciated as luxury art forms. In the sixteenth to nineteenth centuries the work on big rock crystals was as

well-developed in Europe, in particular sites such as Idar-Oberstein, Germany, with an extractive activity of amethyst and agate from the Roman times to the fourteenth century and a continuous manufacture of gemstones. These objects are present also in India, Tibet, and South Asia.

Organic Materials. Amber, different types of fossil resins generally of Cretaceous to Miocene age. There are different sites in the world that have been exploited since ancient times, as in Paleolithic sites in northern Spain, in the Neolithic of Portugal and southwest Spain, where simetite, a typical Sicilian amber variety, was found (Domínguez-Bella 2012). Amber with a greater dissemination and use throughout history is of Baltic origin, with a use at least since the Neolithic in northern Europe and the establishment of routes from the Baltic deposits to the Mediterranean Sea, from the Chalcolithic to Roman times. Rumanite (Rumania), burmite from the Hukawng Valley in Burma, or copal and amber from Mexico, Colombia, and the Dominican Republic were used as gems.

Coral has a gemological use. Red coral was widely used in the Mediterranean during Roman times, as well as pearls, mother of pearl, and tortoiseshell.

Natural glasses. Obsidian, a volcanic glass widely available in many parts of the world, has had a functional and ornamental use throughout history (Kempe and Harvey 1983). There are multitudes of records of its use from Prehistory in the Mediterranean, North and South America, and especially in Mesoamerica, the Middle East and Turkey, and so forth (Rapp 2009).

SEE ALSO: Argon–Argon Dating; Chemistry in Archaeology; Diffraction; Electron Backscatter Diffraction (EBSD); Ethnoarchaeology; ICP-MS and Material Analysis; INAA and Material Analysis; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Infrared Reflectance Spectroscopy; Ion Beam Analysis (PIXE/RBS); Laser-Induced Breakdown Spectroscopy (LIBS); Neutron Activation Analysis (NAA); Optical Spectroscopies; PIXE and Material Analysis; Portable X-Ray Fluorescence Spectrometry

(pXRF); Scanning Probe Microscopy; Synchrotron-Based X-Ray Analytical Techniques and Materials Analysis; TEM and Archaeological Materials; X-Ray Fluorescence Spectrometry (XRF); X-Ray Photoelectron Spectroscopy (XPS); XRD and Materials Analysis

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Glass and Faience

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Glass

Glass is an amorphous solid that, unlike crystalline materials, lacks regularity in the arrangement of its molecular constituents (Figure 1). The glassy state can be obtained through different pathways, but the most common way is the rapid cooling of a liquid under controlled conditions, with an increase in viscosity that prevents crystallization.

Most archaeological and historical glass is composed of a silica (SiO_2) network, a network modifier acting as a flux that lowers the melting temperature of the silica, and a network stabilizer that increases the durability of the glass. The most common source of silica is sand, but quartz and flint can also be utilized. The flux used in glass production varied widely during different periods of time and regions of the world. For example, in the West and Middle East, ashes of salt-tolerant (halophytic) plants which are rich in soda (Na_2O) or potash (K_2O) were predominant ca. 2500–800 BCE. Between ca. 800 BCE and 800 CE, the minerals natron and trona which are rich in sodium carbonates and bicarbonates (and sometimes sulfates and chlorides) were the primary source of flux. After ca. 800 CE, plant ashes returned as the main fluxing material, with the introduction of wood ashes in northern Europe during the medieval period. Calcium oxide (CaO) is a common network stabilizer found in archaeological and historical glass. It can be attributed to limestone or shell fragments (either as impurities in the sand or intentionally added), or through the use of plant ashes. Aluminum oxide (Al_2O_3), another impurity that can be introduced with sand, works also as a network stabilizer. In addition to these three main

glass components, other common additives can include coloring agents such as copper (Cu) and cobalt (Co), decolorizers like manganese (Mn) and antimony (Sb) containing minerals, and opacifiers such as lead antimonate ($\text{Pb}_2\text{Sb}_2\text{O}_7$) and tin oxide (SnO_2) (Henderson 2013).

Glass represents the first manmade translucent solid. It was the last of the three main pyrotechnologies (pottery, metalwork, and glass) to appear, ca. 2500 BCE, in the north of modern-day Syria and Iraq. Initially, it was produced in very small quantities and the earliest objects made were glass beads and other small artifacts (Henderson 2013). The first glass vessels appeared about a thousand years later in Mesopotamia with the invention of the core-forming technique, in which glass threads were spiraled around a clay core that was later removed, followed by mosaic glass, where many pieces of colored glass were fused together and shaped around a core. Blown glass was first developed during the first century BCE in the Syro-Palestinian area and in Italy, soon becoming the dominant technique. During the Roman period, the glass industry became fully established and rapidly spread throughout the empire. Glass technology appeared in the Islamic world since the eighth century CE and the area became famous for its enameling and carving techniques. In the medieval period, glass workshops emerged across Europe that made utilitarian objects following the Roman tradition. Venetian luxury colorless glass, *cristallo*, became highly desirable during the Renaissance, promoting its imitation (*façon-de-Venise* glass), and the development of new glass types such as English lead crystal glass in the seventeenth century (Tait 2004). With the Industrial Revolution, technological innovations greatly expanded the glass industry, some of which included the cylinder process to make sheet glass, and new compositions, such as borosilicate glass, were developed.

Archaeological and historical glass collections are usually studied through typological and stylistic approaches, but classifying glass objects in terms of their formal characteristics

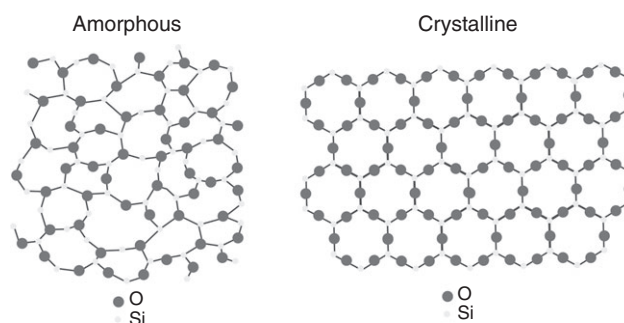


Figure 1 Amorphous structure versus crystalline structure.

(e.g., shape, color, decoration) does not always provide enough information to reconstruct production technology or to develop anthropological interpretations. Crucial information about the material can only be retrieved through scientific methods. Three major approaches dominate the scientific study of archaeological glass: compositional and microstructural characterization, provenance studies, and reverse engineering. Characterization of archaeological and historical glass has proven useful in researching subjects like the technological development of glass production by analyzing changes in raw material selection through time and space (e.g., Brill 1999; Henderson 2013), as well as recycling practices to investigate supply and distribution mechanisms. Characterization is also important to understand the processes of deterioration and to devise ways to conserve glass objects. Provenance studies enable the geosourcing of the raw materials used to make glass and to distinguish between different production groups, making it possible to explore trade networks, and the organization of glass production (Freestone, Ponting, and Hughes 2002). Identifying and quantifying trace elements and determining isotopic signatures are necessary to determine provenance. Differences in trace elements and rare earth elements may represent different raw material sources, while isotope analysis of glass to geosource the raw materials has been focused primarily on the stable isotopes of lead (Pb), oxygen (O), strontium (Sr), and neodymium (Nd) (e.g., Brill 1999; Degryse, Henderson, and Hodgins 2009). Reverse engineering involves the experimental replication of ancient technologies

taking into account characterization and available historical sources, and then the replication products are compared with the archaeological material. Such approach has been applied to better understand glass technology in different contexts.

Interest in the scientific study of archaeological glass is growing worldwide. As more data become available, the study of glass can be performed in a more systematic way and we can begin to look at the larger picture in relation to subjects such as the relationship between organization of production and technological development or the long-distance movement of glass and its associated raw materials within a wider socioeconomic context (Rehren and Freestone 2015).

Faience

Faience is a highly colored vitreous material that consists of a silica-rich body with varying amounts of interparticle glass, coated with an alkaline glaze. Together with glazed steatite and the pigment known as Egyptian blue, it represents one of the earliest manmade vitreous materials. Faience was first produced towards the end of the fifth millennium BCE in the Near East and then in Egypt, expanding later throughout Europe (Tite and Shortland 2008).

The body of a faience object is primarily made with quartz sand or ground quartz. The raw materials commonly used to produce the glaze include crushed quartz, an alkali flux, lime, and colorants. In faience production, there are three main types of flux: soda-rich plant ashes, natron, and mixed alkali. Colorants can

be present in glazes in two forms: metal ions producing transparent colors, and colored particles that yield opaque colors. Examples of metal ions used as transparent coloring agents include copper (blue-green), cobalt (dark blue), and manganese (purple-brown, depending on its oxidation state). Colored particles commonly found in opaque faience glazes are manganese oxides (black-brown), iron oxides (red-black-brown), and lead antimonite (yellow) (Kaczmarczyk and Hedges 1983; Tite and Shortland 2008).

Forming methods of a faience body from quartz paste include hand modeling, shaping over a core, the use of molds coated with lime as the parting layer, and possibly throwing. The faience body can then be glazed using three main methods: application, cementation, and efflorescence (or a combination of these). In the application method, a glazing slurry is first prepared either by direct mixing of the raw materials or by pre-fritting and grinding the mixture. Then the slurry is applied by dipping, pouring onto, or painting the faience body. Once dried, the object is fired and the slurry is turned into a glaze. In the cementation method, the faience body is embedded in a glazing mixture and fired. During firing, the silica in the body reacts with the alkalis in the mixture, forming a glaze over the surface of the body. After cooling, the newly glazed faience object is removed from the partially fused cementation mixture. In the efflorescence method, water-soluble salts are incorporated as raw materials in the faience body. As water evaporates, these salts effloresce on the surface of the body, forming a layer that upon firing becomes a glaze (Vandiver 1983).

Like glass, faience has traditionally been approached through typological and stylistic studies. Although much can be learned by studying faience artifacts in this way, scientific research has greatly enhanced our understanding of this early vitreous material, mainly through characterization and experimental reproduction (e.g., Kaczmarczyk and Hedges 1983; Tite and Shortland 2008; Vandiver 1983). Characterization of faience has mainly focused on the composition of the interparticle glass within the body and of the glaze, as well as on the microstructure of different phases to infer production methods. Experimental reproduction has been carried out extensively, enabling researchers to better

understand faience and its forming technology. In addition, studies focusing on the conservation of vitreous materials have been performed, including faience objects, which are often found in a highly weathered state.

Future directions in faience research may be focused on provenance studies. Some provenance studies of faience glazing materials have been performed (e.g., Kaczmarczyk and Hedges 1983). However, this line of research has yet to reach its full potential. Advancement in provenance studies could shed light on research questions related to organization of production, trade, and exchange within a wider context.

SEE ALSO: Conservation of Vitreous Materials; Deterioration of Vitreous Materials; Glass Color; Glazes, Slips, and Paints

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Glass Color

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Colored glasses were early on valued like gemstones (see GEMSTONES) for their bright colors and later their transparency. The colors have the same physical origin as in mosaic glass tesserae (see CONSERVATION OF MOSAICS), faience (see GLASS AND FAIENCE), glazes (see GLAZES, SLIPS, AND PAINTS), enamels (see CHARACTERIZATION OF METALS AND ALLOYS), and inorganic pigments (see CHARACTERIZATION OF PIGMENTS).

The glass matrix acts as a solvent for dopants (polyvalent transition or rare earth ions). The coloring intensity depends on the sample thickness, concentration of coloring ions, and the transition probability (ϵ) of the valence electrons as they absorb photons from the visible spectrum. The absorbance can be determined by optical spectroscopy. When ϵ is known, the ion's concentration can be quantified from absorption measurements (see optical spectroscopy (see OPTICAL SPECTROSCOPIES) for a schematic of transitions and a list of typical glass colorants and ϵ -values).

Figure 1 shows optical spectra of Co^{2+} (blue) and Mn^{3+} (purple), which are strong colorants ($\epsilon = 200\text{--}135 \text{ L cm}^{-1} \text{ mol}^{-1}$), while spin forbidden transitions of d^5 ions Mn^{2+} (light orange) and Fe^{3+} (light yellow) are much weaker ($\epsilon = 0.3\text{--}5 \text{ L cm}^{-1} \text{ mol}^{-1}$). Charge transfer (CT) transitions from oxygen-anion to metal-cation have much higher transition probabilities (ϵ approximately several thousands), but usually their absorption maximum stays in the ultra-violet (UV) range and only contributes to the absorption edge. The $\text{S} \rightarrow \text{Fe}^{3+}$ transition in reduced melted sulfide-containing glasses lies in the visible range, causing amber to brown color. Intervalence-charge transfer (IV-CT) transitions between two metal cations of different charge, for example $\text{Fe}^{2+} \rightarrow \text{Fe}^{3+}$ or $\text{Fe}^{3+} \rightarrow \text{Mn}^{2+}$, move further into the visible wavelength region. In glasses,

the ions' proximity for the transfer of electrons is only attained for high dopant concentrations. IV-CT transitions are of similar intensity as CT transitions and glasses with several weight percentage (wt%) of differently charged polyvalent ions often appear black. An anion-anion charge transfer within S_3^- causes the deep blue color in lapis lazuli gemstones.

Optical spectroscopies can resolve multiple colorants: for example, the combination of blue Fe^{2+} and yellow Fe^{3+} ions in green-colored glasses. Many colorful ions were only introduced to glasses in the last centuries: for example, green Cr^{3+} , yellow Cr^{6+} , blue-green V^{4+} , green-yellow V^{3+} , brown Ni^{2+} (purple-bluish in lead silicate), yellow-green UO_2^{2+} (strong fluorescence (FL)), violet Nd^{3+} (FL), and Pr^{3+} (FL). No dissolved ions give a bright red color in glasses. Deep red ruby glasses contain metal colloids, that is, silver or copper nanoparticles, which absorb photons by plasmon resonance. While scattering can be neglected for small particles of less than 50–60 nm diameter, larger particles can induce dichroism or appear opaque (Tilley 2011).

Preparation of ruby glasses is challenging, since ruby glasses are still colorless after melt quenching, containing ionic solutions of Au or Cu ions. The precious metals are reduced to the metallic state (nucleation) under subsequent reheating (often enhanced by redox agents, e.g., organics, Sb_2O_3 , or SnO). Nanoparticles grow upon consecutive heating and since the color depends strongly on the size, number, and shape of the particles, time and temperature of the secondary treatment is crucial. SnO_2 might be added to prevent coagulation of the metallic colloids (Vogel 1992).

Ruby glasses are often so deeply colored that a thin colored layer on a transparent support (flashed glass) is often sufficient. Analogously, thin ruby-red striae serve as vibrant colorant in red church windows (Kunicki-Goldfinger et al. 2014).

A two-step production process is also exploited in silver stained glasses. Silver is not added to the batch, but Ag-salts are painted locally on one

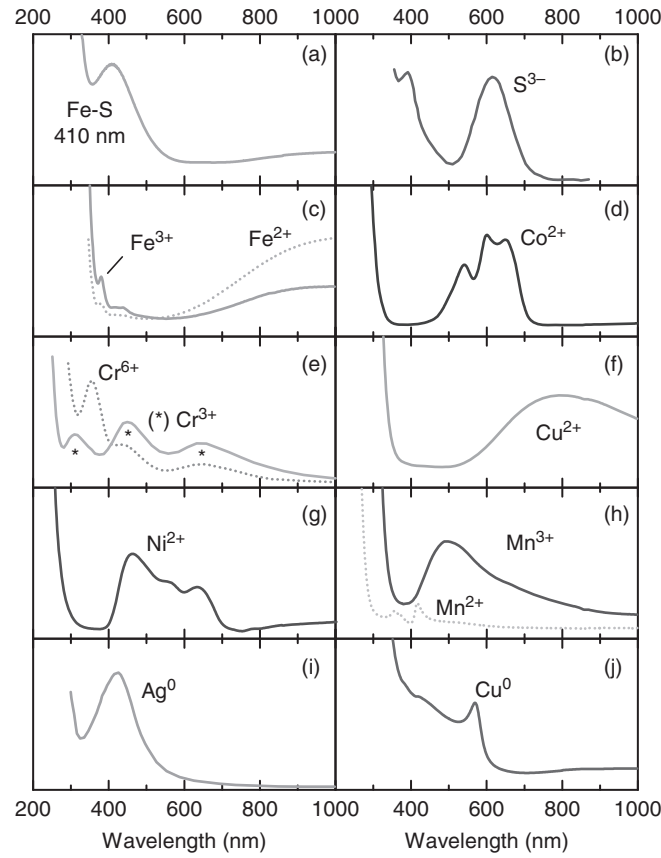


Figure 1 Selected absorption spectra: (a) inter-valence-charge-transfer transition (IV-CT) from sulphide anion to iron ($S^{2-} \rightarrow Fe^{3+}$), and (b) anion charge-transfer of S^{3-} in lapis lazuli. (Stauber et al. 2016); (c to h) d-d transitions in soda-lime-silicate glasses with (c) Fe^{2+} (d^6) broken, and Fe^{3+} (d^5) solid line; (d) Co^{2+} (d^7); (e) Cr^{3+} (d^3) solid line, and Cr^{6+} (d^0) broken line; (f) Cu^{2+} (d^9); (g) Ni^{2+} (d^8); (h) Mn^{2+} (d^5) broken, and Mn^{3+} (d^4) solid line; (i, j) plasmon resonance of metallic nanoparticles (i) Cu^0 and (j) Ag^0 (Perez-Villar et al. 2008).

glass slide. Upon heating, ion exchange occurs between the applied Ag^+ ions and the alkali ions in the glass. Subsequent reduction to metallic silver gives the same reaction as discussed for ruby glasses. For silver particles, the colors range from pale lemon to dark orange (Vogel 1992) (see OPTICAL SPECTROSCOPIES and Figure 1).

In striking or cutoff glasses, the intrinsic UV-absorption shifts into the visible wavelength region, as differently sized Cd-chalcogenides precipitate. Initially, the glasses appear light yellow to colorless, and only controlled reheating and precipitation of nanocrystals induces saturated colors (see OPTICAL SPECTROSCOPIES).

In lead glasses, highly polarizable Pb^{2+} ions shift the absorption edge to longer wavelengths, resulting in a light-yellow coloring. When doped with blue chromophores (i.e., Cu^{2+} or Co^{2+}) a greenish glass color ensues.

In glazes or glass mosaic *tesserae*, colored microcrystalline pigments, such as Naples yellow ($Pb_2Sb_2O_7$) or Egyptian blue ($CaCuSi_4O_{10}$), can act as chromophores. Crystalline pigments can be identified by their fingerprint Raman spectra. The same inorganic pigments known in glasses, glazes, and enamels are also present in many paintings. Because microcrystals cause scattering, such colored materials lose their transparency. Generally, opacification ensues whenever small particles

are dispersed in a vitreous matrix with different refractive index. These particles might be crystalline (e.g., CaSb_2O_6 , TiO_2) or amorphous (e.g., phase separation, air bubbles). Depending on the particle sizes, different types of opacification can be distinguished (see OPTICAL SPECTROSCOPIES).

A different color phenomenon is photoluminescence, as a material emits light of certain wavelengths after excitation with photons. Typical examples include red emission for octahedral Mn^{2+} or green emission for tetrahedral Mn^{2+} . Sn^{2+} , Cu^+ , Sb^{3+} , or Pb^{2+} ions all emit light blue light when excited with UV light. Defined excitation and emission spectra allow the unambiguous analysis of these ions (for more details see PHOTOLUMINESCENCE OF EGYPTIAN BLUE).

Mn ions often affect deterioration (see DETERIORATION OF VITREOUS MATERIALS) and conservation of glasses (see CONSERVATION OF VITREOUS MATERIALS), either through photo-oxidation of nearly colorless Mn^{2+} under UV or sunlight to purple-colored Mn^{3+} , or by microorganisms which transform Mn ions into MnO_2 . Corrosion layers often look white due to light scattering at pores, crystalline salt precipitates, or iridescent

when light is refracted in thin corrosion layers of lower refractive index.

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Glazes, Slips, and Paints

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In the field of ceramics, the terms “glaze,” “slip,” and “paint” designate three different types of coating that are applied on the surface of unfired or once-fired (biscuit-fired) ceramic bodies for decorative or functional purposes. This entry provides an overview of the composition and different applications of glazes, slips, and paints in archaeological ceramics and outlines the primary scientific techniques used for analyzing them by reviewing examples of previous studies.

Glazes

The glaze is essentially a layer of glass (see GLASS AND FAIENCE) that provides a smooth, impermeable ceramic surface after firing and enhances the mechanical strength of the ware by the creation of a body-glaze interaction layer (also known as the “buffer layer”).

Chemistry

The structure of glaze is similar to that of glass, and consists of network formers, network stabilizers, and fluxing agents. In archaeological glazes, the principal network former is silica (SiO_2), with alumina (Al_2O_3) playing an important role as the main network stabilizer. Common fluxing agents are alkalis (Na_2O and K_2O), earth alkalis (CaO and MgO), lead oxide (PbO), and boron oxide (B_2O_3). Each flux has its own individual characteristics and largely contributes to some of the primary features of the glaze, such as its firing temperature and its viscosity in the molten state. Hence, the nomenclature used to describe glazes has been based on the dominant fluxing agents present in the glaze composition: for instance, “alkali glazes,” “lime glazes,” “lime-alkali glazes,” or “lead glazes.”

Glazes may also contain metallic oxides as colorants. The color produced by a certain metallic ion depends on various factors, including its positioning in the atomic structure of glaze, the oxidation or reduction atmosphere of firing, and the temperature of firing. The composition of the base glaze also has a direct effect on the coloration of a certain metallic oxide. For instance, copper oxide is a blue or turquoise color in highly alkali glazes, but it becomes green in lead glazes. In reduction, copper oxide tends to black, and in extreme reduction to red. Manganese oxide produces a purple color in oxidization, but tends to brown as the atmosphere becomes reduced. Iron oxide, depending on the conditions, covers a variety of tints from pale green, to yellow/brown, to purple, and black.

“Under-glaze” or “on-glaze” (also “over-glaze”) techniques may be used in the decoration of glazed ceramics. Under-glaze decoration involves the application of paint or slip on a usually, but not necessarily, biscuit-fired body that is then covered with a transparent glaze. The technique is discussed further below under “Slips” and “Paints.” On-glaze decoration, on the other hand, is applied on top of a fired glaze. The ware is again fired, but at low temperatures (usually between 500 and 800 °C), below those employed to mature the glaze itself. On-glaze enamels are formed of a mixture of silica, coloring oxides, and low-melting fluxes, such as oxides of lead and boron. During the enamel fire, the on-glaze colors are fused onto the glazed surface. An example of enameled glazed pottery is the “Minai ware” of Persia which was produced for a short period between the late twelfth and early thirteenth centuries (Wen and Pollard 2016). Luster is another type of on-glaze decoration which was used in the Near East since the ninth century CE and in Europe (mostly Spain and Italy) since the thirteenth century. The production of luster is a complex process that involves painting a copper- and/or silver-containing compound over the glaze and firing under reducing conditions to temperatures between 500 and 600 °C. The ionic exchange between the luster and the glaze layers

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results in a uniform dispersion of copper and silver nanoparticles at the top surface of the glaze, which provides an iridescent metallic appearance (Pradell et al. 2008).

Transparency and opacity are two other important characteristics of ceramic glazes. If fired to the maturing point and fully fused, the majority of glazes will become transparent or nearly so, and the body behind the glaze can be clearly seen. In some other glazes, opacity is a preferred feature in order to completely disguise the color of the body. Three main methods appear to have been used by craftsmen to render less transparent, translucent, or opaque glazes: by underfiring the glaze, by the development of secondary crystals in the molten glaze, or by the addition of opacifiers to the glazing recipe. In an underfired glaze, air bubbles and relics of raw materials remain as undissolved, suspended particles that obstruct the passage of light and thus render translucency. A similar effect was produced by the formation of secondary crystals during firing or slow cooling of a glaze. Both techniques and combinations of them were employed in some of the Parthian (247 BCE–224 CE) and Sassanian (224–651 CE) glazes in the Near East (Pace, Prevot, and Mirti 2008); however, it is not clear whether this was an intentional effect or not. In order to produce a fully opaque glaze, opacifying crystals were added to the glazing mixture. The crystals may have retained their primary structure and remained undissolved during firing, or have dissolved during firing and then recrystallized. In addition to their opacifying effects, these crystals act as colorants. An early application of this technology was in ancient Mesopotamian polychrome glazed bricks, using crystals of lead antimonate ($\text{Pb}_2\text{Sb}_2\text{O}_7$) and calcium antimonite ($\text{Ca}_2\text{Sb}_2\text{O}_7$) to produce opaque yellow and opaque white glazes. From around the eighth century CE in the Levant and the Near East, lead-tin oxide (lead stannate; PbSnO_3) and tin oxide (SnO_2) began to be used in opaque yellow and opaque white glazes. The invention of tin oxide opaque glazes had a major impact on ceramic traditions by providing a fine, smooth, white background over which a variety of colored glazes or other on-glaze decorations could be applied. The technique became prevalent in the Near East from the eighth to the nineteenth centuries CE, and was adopted in Europe from around the thirteenth

to the eighteenth centuries CE, where it gave rise to the production of “majolica,” “faience,” and “delftware.”

Classification of archaeological glazes

The earliest glazes appeared on nonclay bodies. Glazed siliceous stones, such as quartz and quartzite, and glazed steatite were produced from the fifth millennium BCE in Egypt, the Near East, and the Indus Valley. Sometime during the late fifth millennium BCE, the production of so-called Egyptian faience began in the Near East and Egypt. The glazes were broadly of the alkali- or earth-alkali-based compositional types and colored by copper, although some samples of faience have also been found to include cobalt and manganese-iron pigments.

The first glazed clay objects were produced around the middle of the second millennium BCE in the Near East. The composition of these glazes was alkali and remained as such until the eighth/ninth century CE when lead oxide was added to the glaze recipes of the Levant and the Near East. It seems that in all of these cases, the lead oxide was associated with tin oxide for the purpose of glaze opacification. The combined lead-alkali opaque glazing tradition transferred from the Levant and the Near East to North Africa and Europe and continued in both the Near East and Europe until the nineteenth century, when concerns regarding the poisonous properties of lead oxide increased. The first manufacture of lead glazes, however, predates their emergence in the Near East. Lead glazing in China began in the fifth century BCE and became current practice during the Han dynasty (206 BCE–220 CE). Lead glazes were also widespread throughout the Roman and Byzantine worlds.

In the Far East, another family of glazes was developed around 1500 BCE. These glazes were in principle different from those in the Near East in that they matured at higher temperatures (up to around 1300°C) and contained higher amounts of alumina (Al_2O_3). The earliest glazes are believed to have been accidentally fluxed with lime in the form of wood ash from the kiln fireboxes and are thus commonly referred to as “lime glazes” or “wood ash glazes.” Subsequently, lime-rich ashes were intentionally added to the clay by potters

to produce glazing mixtures. The color of early lime glazes was brown to grayish green from iron oxide impurities present in the raw materials. A later development in Chinese glazes took place during the early western Zhou period (1046–771 BCE) when potash (K_2O)- and soda (Na_2O)-rich fluxes and minerals were added to the glazes used on stonewares and porcelains.

Methods of analysis

Scanning electron microscopy (SEM) combined with quantitative elemental analysis has increasingly become the technique of choice for investigating both the microstructure and chemical composition of archaeological glazes. As discussed above, glazes are often inhomogeneous structures due to the presence of undissolved grains, secondary crystals, and opacifying particles, as well as areas of weathering. It is therefore extremely important to study the microstructure of glazes—that is, the shape, size, and distribution of different phases—to reconstruct the technological processes of production and to target specific areas of interest for chemical analysis. Samples are prepared as cross-sections from the glaze layer into the body. This approach enables examination of the body–glaze interaction layer as well as the glaze itself. To give but one example, SEM coupled with energy dispersive spectroscopy (SEM-EDS) examination of early Islamic (seventh/eighth century CE) opaque yellow glazed wares from Egypt and Syria showed that the glazes were of the very high lead compositional type (containing ~60 wt% PbO) and opacified by lead–tin oxide crystals ($Pb(Sn,Si)O_3$). These observations suggested that the production technology of early Islamic opaque yellow glazed wares was likely connected to Byzantine opaque yellow glass-making, on the one hand, and early Islamic opaque white glaze-making, on the other (Tite et al. 2015).

A number of nondestructive methods can also be used for chemical analysis of archaeological glazes. However, because evaluation of the microstructure is not possible with these techniques, there is the risk that the analyzed areas might indeed be parts of the weathered zones or crystalline phases in the glaze. This has to be taken into account when interpreting

data. In the study of early Islamic opaque yellow glazed wares by Tite et al. (2015), portable X-ray fluorescence spectroscopy (pXRF) (see PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)) and particle induced X-ray emission (PIXE) (see ION BEAM ANALYSIS (PIXE/RBS)) (see PIXE AND MATERIAL ANALYSIS) techniques were also used for analysis of glazes from Egypt, Syria, Iraq, and Iran. The resulting data confirmed that the opaque yellow glazes were all of the same compositional type and had adopted similar technological processes.

Slips

The slip, also known as “engobe,” is a mixture of fine-grained clay and water that can be applied to ceramic bodies before firing using two different methods: first, painted directly onto the body using a brush to produce surface patterns that stand in contrast to the background, and second, applied as an overall surface finish to disguise the body by dipping or pouring the slurry over the piece. The first method was a common practice in prehistoric and early historic wares. Elaborate examples of this technique are the ancient Greek black- and red-figure pottery. The iron oxides present in the clay minerals of the slips went through a cycle of oxidizing–reducing–oxidizing in a single firing process, resulting in the black (reduced) and red (oxidized) colors in the final product (Noble 1966).

Application of slips as overall coatings is best represented in the red slip Terra Sigillata wares of the Roman period from North Africa, west Turkey, and Cyprus. From the Early Byzantine period in the eastern Mediterranean, potters began to cover slipped wares with a transparent glaze. Further decorative styles developed by incising through the slip applied to the body before glazing so as to reveal the body beneath. The technique, commonly known as Sgraffito, or Sgraffiato, became widespread from the tenth century CE in the northern and eastern Iranian World and in Fatimid Egypt. In the Iznik pottery of the Turkish Ottoman empire produced from the late fifteenth century, a white slip was used to provide a smooth background for color pigments to be painted before glazing.

Similar to the study of ceramic bodies, the main approach to study slips has been based on their microstructure. Microstructural observations of slips are usually carried out using optical microscopy (see OPTICAL MICROSCOPY). SEM is also used to identify the chemical composition of the inclusions in the slip layer. The application of these methods to study the slips of tenth-century wares from Merv, Turkmenistan, resulted in provisional classification of the wares based on the different microstructures and compositions of the slip clays (Casellato et al. 2007).

Paints

Ceramic “paints” are water- or oil-based suspensions of powdered pigments, generally—but not necessarily—together with fine-grained clay, and an organic binder (see PIGMENTS AND BINDERS), such as vegetable gum or resin, or animal glue. Paints are applied to decorate ceramic surfaces usually using a brush, stick, or the finger. The majority of pigments used in prehistoric and early historic pottery were inorganic minerals that were applied to ceramic bodies before or after firing. Of these, iron-rich minerals were among the most abundantly used for painted decorations in brown (limonite, $\text{FeO}(\text{OH})$), red (hematite, Fe_2O_3), and black (magnetite, Fe_3O_4 , or ilmenite, FeTiO_3). Manganese-rich minerals such as pyrolusite (MnO) were also used for hues of black and brown. For green and blue decorations, copper-rich minerals such as malachite (CuCO_3) and azurite were used. Both pigments become unstable upon heating and were therefore used only on fired ceramic bodies. In addition to mineral pigments, organic pigments were used on fired ceramic bodies: for instance, charcoal for black decoration and burned bone ($\text{Ca}_3(\text{PO}_4)_2$) for white decoration.

Pigments could also be artificially made. The so-called Egyptian blue and Chinese purple are two synthesized pigments of earth alkali copper silicate composition (Wiedemann and Berke 2001). Egyptian blue is the artificial equivalent of the mineral cuprorivarite ($\text{CaCuSi}_4\text{O}_{10}$), which was produced in antiquity by firing a mixture of quartz, lime, a copper compound, and an alkali flux. Egyptian blue paints were more extensively

used in the decoration of tombs and temples and less extensively on pottery. Chinese purple with the formula $\text{BaCuSi}_2\text{O}_6$ is also an artificial pigment with no mineral equivalent in nature. The pigment was used in the paints of the Qin Shihuang's (259–210 BCE) terracotta army and in pottery during the Han dynasty (206 BCE–220 CE). Another well-known artificial pigment is the “Maya blue” which is a combination of indigo, an organic pigment, and palygorskite, a natural clay (José-Yacamán et al. 1996). Maya blue paint was widely used on pottery, murals, and sculptures by the ancient Mayas and other people in Mesoamerica.

Raman spectroscopy (see RAMAN SPECTROSCOPY) offers a unique nondestructive tool for identification of pigments. A number of other instrumental techniques such as X-ray diffraction (XRD), X-ray fluorescence spectroscopy (XRF) (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), and SEM have also been widely used to study pigments in ceramic paints. For characterization of the organic binder, gas chromatography (see CHROMATOGRAPHY AND ARCHAEOLOGICAL MATERIALS ANALYSIS) and Fourier transform infrared spectroscopy (FTIR) (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)) have been the two main analytical methods of choice. A combination of these techniques was employed in a series of studies to identify the various pigments and the binding media of the paints applied on China's terracotta army in Xiangshan (e.g., Wei, Ma, and Schreiner 2012).

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ICP-MS and Material Analysis

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ICP-MS instrumentation

An inductively coupled-plasma mass spectrometer (ICP-MS) consists of five main components: an introduction system, a plasma ion source, an ion transfer interface, a mass analyzer (mass separation device), and detector(s). Liquid, solid, or gas samples are introduced in the plasma source via the introduction system. The source of the ICP is a high-temperature (6,000–8,000 K) argon plasma. Samples introduced in the argon plasma are rapidly vaporized, atomized, and converted into positively charged ions. The ions enter the mass spectrometer through a sampler and a skimmer cone. Following the skimmer cone, the beam of ions is steered by the ion lenses of the ion transfer interface into the mass analyzer. The mass analyzer separates the ions based on their mass-to-charge ratio (m/z). The most common type of mass analyzer used in commercially available ICP-MS instruments is the quadrupole mass filter. The quadrupole (Q) consists of four charged rods that generate a dynamic electrostatic field that allows ions of selected m/z to pass through the analyzer and reach the detector. The detection capabilities of Q-ICP-MS can be severely affected by formation of polyatomic interferences. Some Q-ICP-MS are equipped with a collision/reaction cell to break down the spectral polyatomic interferences before the ions of interest enter the quadrupole mass filter. Double-focusing magnetic sector mass analyzer is used in high-resolution (HR)-ICP-MS and multicollector (MC)-ICP-MS. These magnetic-sector instruments use an electromagnet and an electrostatic analyzer to separate the ions based on their m/z . The advantage of the HR-ICP-MS is higher resolution and higher sensitivity when compared to traditional Q-ICP-MS. A specialized type of

magnetic sector instrument, the MC-ICP-MS, is fitted with multiple detectors and is used exclusively for high-precision isotope analyses. The detector converts the arriving ions into electrical pulses. The magnitude of the electrical pulses is directly dependent on the concentration of the element in the sample. The two most common types of detectors used in the ICP-MS instruments are secondary electron multiplier (SEM) and Faraday detectors. Modern SEM detectors provide high sensitivity and very wide ($>10^9$) dynamic range of detection. Faraday detectors are used with high ion signals for high-precision isotope analyses. Q-ICP-MS and HR-ICP-MS are most commonly fitted with a single SEM detector. MC-ICP-MS are fitted with multiple Faraday and SEM detectors.

ICP-MS material analysis

A wide variety of samples, including water, oils, soils, rocks, ores, metals, artifacts, ceramics, construction materials, plants, bones, teeth, fur, and hair, can be analyzed with ICP-MS. As sample molecules are atomized and ionized in the high-temperature plasma, the ICP-MS provides exclusively elemental concentration and/or isotope ratio information. Almost all elements in the periodic table, with some exceptions such as H, He, N, O, and Ar, can be quantitatively measured to sub parts per million (ppm) levels with ICP-MS. Depending on the relative abundances of elements in the samples, the ICP-MS data are reported as major (percent level) and trace (ppm or lower level) elements. It is recommended that sample preparation is performed in a clean laboratory environment with ultra-pure reagents to avoid sample contamination. Different sample preparation protocols are available for ICP-MS analyses. Samples containing silicates, such as soils, rocks, obsidian, and pottery, require digestion with hydrofluoric (HF) acid. Ores, metals, and skeletal material typically require dissolution in nitric (HNO_3) acid. Plants, including archaeological wood samples, can be ashed first and then the ash is dissolved with acids. Microwave

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digestion is also used for organic-rich samples. The most common method for quantification of the results is via external calibration based on standards. Isotope dilution and standard addition are other methods used for quantification of the ICP-MS results. Single or multi-element solution standards or solid materials (rock, glass, clay, bone standards) are available for external calibration.

The concentrations of major and trace elements in archaeological artifacts can be used to provide information about provenance, resources, crafts, and trade in the past. For example, elemental concentrations in pottery and metal artifacts can be used to estimate the type of raw materials, methods of production, and circulation and exchange patterns (see CHARACTERIZATION OF METALS AND ALLOYS and CHARACTERIZATION OF CERAMICS). Trace elements in natural materials such as obsidian and chert can provide information about provenance and trade (see CHERT, SILEX, AND OBSIDIAN SOURCING). Similarly, trace elements in glasses can provide information about their origin and trade patterns in the past (Degryse and Vanhaecke 2016). Elemental analyses of biological materials such as bones, teeth, and hair can be used for estimation of diet (see DIET AND TRACE ELEMENTS), exposure to heavy metals in the past, and postmortem alteration. In particular, elevated concentrations of rare-earth elements and uranium in bones indicate postmortem elemental uptake. Tooth enamel is the preferred material for elemental and isotope analyses, as it is more resistant to postmortem diagenetic changes. The primary composition of other artifacts (e.g., metal or glass) also can be altered due to corrosion and weathering. In addition, an issue a researcher must consider when working with elemental and/or isotopic data is mixing between various sources. For example, metal artifacts can be made with ores from several deposits and/or by recycling of older artifacts (MacFarlane and Lechtman 2014).

Laser ablation (LA) ICP-MS

The ICP-MS can be coupled to a laser ablation (LA) unit for a direct, virtually nondestructive method for spatially resolved (approximately

10–100 microns) chemical analysis of solid archaeological samples (Degryse and Vanhaecke 2016). In this method a small volume of the sample is ablated by a focused laser beam and the resultant sample aerosol is transported by a carrier gas (usually He) to the plasma source of the ICP-MS. Although the ablated area of the sample is micron-sized, the artifact needs to be small enough to fit inside the ablation cell. Alternatively, a custom-made ablation cell can be mounted with adhesive material on the surface of precious artifacts that cannot be subsampled. Although LA-ICP-MS analysis is a virtually non-destructive method for chemical analyses of solid samples, it provides chemical information for a micron-sized area. Therefore, LA can be used for bulk chemical characterization of only homogeneous materials such as glass, obsidian, porcelain, and metals. Bulk composition of heterogeneous materials such as pottery or stone objects is better characterized by dissolution ICP-MS analysis. However, the spatially resolved analysis by LA can be used to “map” elemental distribution within heterogeneous samples. For example, in pottery provenance studies LA-ICP-MS can be used to analyze clay, temper, and glaze components separately and so provide detailed information about the origin of raw materials and method of production. Furthermore, altered, weathered, or corroded areas of artifacts can be avoided by the spatially resolved LA analysis. In addition, LA can be coupled with MC-ICP-MS to obtain in situ isotope information.

MC-ICP-MS isotope analyses

MC-ICP-MS is used exclusively for high-precision isotope ratio analyses. The multidetector configuration allows for simultaneous acquisition of all isotope ion signals for a given element of interest. A number of isotope systems, such as Li, B, Mg, Si, Fe, Cu, Zn, Sr, Ag, Sn, Sb, Nd, Hf, Pb, and U, can be measured with very high precision and accuracy with MC-ICP-MS. Similar to ICP-MS, samples can be introduced in the MC-ICP-MS in solution form or directly as solids via LA. Ultimate precision and accuracy is achieved in solution analyses. It is mandatory that sample preparation for isotope analysis is

performed in a clean laboratory environment using ultra-pure reagents. Following sample dissolution in acids, the element of interest for isotope analysis must be purified by ion-exchange chromatography to remove interfering elements. For example, Sr is purified on “Sr-Spec Resin” to remove matrix and interfering elements such as Rb because ^{87}Rb cannot be resolved from ^{87}Sr even with the highest resolution possible on HR-ICP-MS. In addition to isobaric interferences, the isotope ratio measurement is strongly affected by instrumental mass-bias (fractionation of the isotope ratio due to instrumental effects). If available, an internal stable isotope pair with known isotope abundances is used for fractionation correction. If there is no available stable isotope pair (e.g., Li isotopes), then a standard with known isotope abundances is measured before and after each sample. Then the sample isotope data are corrected based on the standard measurements. A third method for mass-bias correction is via the addition of another element (a spike) with known isotope abundances and close mass to the element of interest. For example, this is the most widely used method for high-precision Pb isotope analyses on MC-ICP-MS. In this method, the purified Pb from the sample is spiked with $^{203}\text{Tl}/^{205}\text{Tl}$ just before introducing the sample in the MC-ICP-MS (Kamenov, Mueller, and Perfit 2004).

In-situ isotope information for solid samples can be obtained directly by LA-MC-ICP-MS. Overall, the precision and accuracy of the LA-MC-ICP-MS isotope measurements is inferior in comparison to solution analyses due to matrix effects, presence of interfering elements, and the large corrections required to calculate the true isotope ratios.

The isotope ratios provide powerful information for identifying provenance, resources, and trade in the past. For example, Pb isotope analyses of metal artifacts, ancient coins, and glaze paints can provide information about the ore deposits mined in the past to extract the metals (Desaulty et al. 2011; MacFarlane and Lechtman 2014). Furthermore, as the isotopes can differentiate one metal supply from another, they also provide information about provenance and trade. Isotope analyses of biological materials such as bones, teeth, and hair are used for estimation of place of origin, mobility, and diet.

For example, Pb and Sr isotopes in human or animal teeth can be compared to known ratios in the bedrock of a given geographical area and this information can be used for identification of the place of origin and migration patterns of the individuals (see MOBILITY AND LEAD ISOTOPES and MOBILITY AND STRONTIUM ISOTOPES). In addition, nontraditional isotopes such as Fe, Zn, and Cu and stable pairs of traditional isotopes (e.g., $^{88}\text{Sr}/^{86}\text{Sr}$) measured with MC-ICP-MS can potentially provide new insights for the origin of archaeological materials and individuals' diet (Knudson et al. 2010; Desaulty et al. 2011). Furthermore, MC-ICP-MS can be used for dating in archaeology by measuring U-series (see URANIUM-SERIES) and U-Pb isotopes (Balter et al. 2008).

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INAA and Material Analysis

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INAA is a method for determining the elemental composition of materials by neutron activation analysis (NAA) in a purely *instrumental* manner that requires no chemical preparation of the material to be analyzed. The capabilities of INAA are unique and uniquely suited for relating archaeological materials to geographical/geological areas. Most data available today on archaeological material such as pottery and obsidian are based on INAA. There is a vast literature on the use of INAA in the fields of archaeology, agriculture, biology, chemistry, cosmochemistry, forensic science, geology, medicine, nuclear chemistry, and more generally, material science.

The analysis of material for the concentration of elements by NAA dates to 1936 and is attributed to George de Hevesy and Hilde Levi. They were able to identify elements through neutron-induced radioactivity. Developments in nuclear technology, the accumulation of data on the nuclear properties of the elements and their isotopes, the development of the energy-dispersive germanium detector, coupled with digital computers and software for spectrum analysis, all made INAA a powerful analytical tool for element detection and quantification for material, including the chemical “fingerprinting” of basalt, clay, faience, flint, glass, limestone, marble, obsidian, pottery, pumice, gemstones, and precious metals.

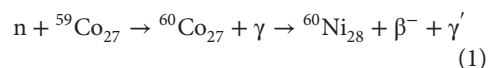
The salient characteristic of INAA for determining element concentrations is that no chemical preparation of the sample is required. There are few or no matrix effects arising from the interaction of gamma-ray photons with the sample matrix. Many elements exhibiting different chemical behaviors can be measured simultaneously. Errors can be precisely calculated, with

outstanding inter-laboratory comparability and intra-laboratory reproducibility.

The amount of material needed for analysis by INAA is typically 100–200 mg, but excellent results can be obtained with smaller samples. Samples are subjected to neutron irradiation in a nuclear reactor and subsequently withdrawn for measurement.

As applied to archaeological artifacts, neutron activation almost always refers to activation by “thermal” neutrons. The term “thermal” refers to the fact that these neutrons have a kinetic energy distribution with a mean energy of 0.025 eV, corresponding to a temperature of 293 K (20 °C). The source of the neutrons is the fission that occurs in the reactor fuel ($^{235}\text{U}_{92}$). Fission neutrons have a mean energy of approximately 2 MeV, but high-energy neutrons are not as effective in sustaining the chain reaction as are thermal neutrons. The neutron energy is reduced by scattering in a moderating material that surrounds the nuclear reactor core. Through multiple scattering in the moderator, the neutrons lose most of their energy and come into thermal equilibrium with the moderator. While most of the neutrons are thermalized, there is a significant number of neutrons with higher energies, and these can be utilized in INAA involving a different type of reaction than that with “thermal” neutrons.

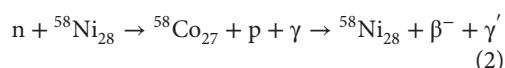
The “thermal” neutrons undergo neutron capture reactions in which the nucleus of an atom absorbs a neutron. If the newly-formed isotope is radioactive, its decay is accompanied by the emission of gamma rays, and so the atom can be detected through the associated gamma-ray spectrum which is unique to every nucleus. Thus every element can be identified and quantified, providing only that neutron capture results in a radioisotope whose decay is accompanied by the emission of gamma rays. An example of a neutron capture reaction that makes cobalt (Co) easily detectable is:



The first gamma ray (γ) after the arrow in reaction (1) appears with the neutron capture and is characteristic of the nucleus formed by the neutron capture ($^{60}\text{Co}_{27}$). This prompt gamma ray forms the basis of an analytical method known as prompt gamma-ray INAA. To utilize the prompt gamma rays, neutrons are extracted from the nuclear reactor and directed at the material under analysis. This method may be used to analyze archaeological objects nondestructively. The second gamma ray after the arrow (γ') in reaction (1) appears with the disintegration of the radioisotope formed by neutron capture, and is characteristic of the resulting isotope ($^{60}\text{Ni}_{28}$). This delayed gamma ray is the basis of what is usually meant by INAA as applied to archaeology. The β^- (beta ray) is the electron emitted by the radioisotope.

A small percentage ($\sim 1\%$) of the neutrons in a reactor have energies in the range 0.025–100 eV. These epithermal neutrons can be absorbed by some nuclei and they form the basis of epithermal NAA (ENAA): this is INAA based on the delayed gamma rays following epithermal neutron capture.

The high-energy tail of the neutron energy distribution has a small but significant number of high-energy (>1 MeV) neutrons. These neutrons cause a nuclear reaction in which a neutron goes into a nucleus and a nucleon (proton or neutron) is emitted, as, for example, in reaction (2) below, where n is the incoming neutron, p is the outgoing proton and γ is a prompt gamma ray:



Analysis of material based on the gamma-ray spectrum associated with high-energy neutrons is called fast neutron activation analysis (FNAA). Fast neutrons can be extracted from the nuclear reactor and directed at a target that can then be analyzed nondestructively. If the element formed by a reaction such as (2) is radioactive, delayed gamma rays (γ') will also be present as in (2), and thus some FNAA (as well as ENAA) always accompanies “thermal” neutron INAA.

The great advantage of INAA by delayed gamma ray is that the activation and measurement processes are spatially and temporally separated. The gamma-ray spectrometry can be carried out in a low background environment

away from the nuclear reactor site. Furthermore, the time of measurement can be chosen to optimize the precision for particular sets of elements, based on the half-life of the radioisotopes involved.

The concentration of an element is related to the intensity of the gamma ray associated with that element. The smallest concentration of an element that can be measured by INAA depends on the intrinsic physical properties of the nuclei participating in the reaction, the natural abundance of the isotope capturing a neutron, the complexity of the material and external factors, such as the properties of the detector system, and the neutron flux. Many trace elements present in archaeological materials can be measured routinely by INAA with a precision of $\ll 1$ $\mu\text{g/g}$. As many as 73 elements (major, minor, and trace) can be measured by INAA.

In order to deduce the absolute concentration of an element from the gamma-ray intensity it is necessary to employ standards of known composition that are neutron-activated simultaneously with and under identical conditions as the samples under analysis. The absolute accuracy depends on the accuracy inherent in the standard. An alternative to the use of a multielement standard is the comparator method. Multielement standards are employed in most archaeological studies.

The first INAA applications to ancient ceramics were reported in the mid-1950s at the Brookhaven National Laboratory (USA). In the mid-1960s a high-precision INAA program was undertaken at the Lawrence Berkeley National Laboratory (USA). Other INAA provenance programs followed (Speakman and Glascock 2007).

An example of an early and important success of INAA in elucidating the origin of pottery was reported in 1973 and involved Palestinian bichrome ware. This pottery, which appeared in the second millennium BCE, was long thought to have originated from the coast of ancient Palestine. INAA showed that the pottery actually originated from Cyprus (Artzy, Asaro and Perlman 1973).

M. Parker conducted excavations in Jerusalem (1909–1911) and his findings were debated for decades. In particular, a small black and red burnished bowl from a tomb presented archaeologists with a paradox that was debated for

nearly a century. While most objects in the tomb could be dated to the late fourth millennium BCE (Early Bronze I) and were locally made according to stylistic considerations, the bowl, by scholarly consensus, was judged to be a Cypriot import on the basis of style. But the style of the bowl belonged to a different age, about a thousand years later (Middle Bronze I), than other objects in the tomb. Unraveling this mystery had important implications for understanding foreign relations in the Middle Bronze I. A study involving INAA provided unequivocal proof that Parker's controversial bowl was locally made and had no bearing on Cyprus (Maeir, Yellin and Goren 1992).

A further example of how INAA can resolve issues of pottery origin concerns the Chariote Krater of Tel Dan (Israel), so-called because the krater is decorated with a chariot procession. The krater was found in a tomb along with other objects that dated the tomb to the fourteenth century BCE on stylistic grounds. For many years there was a debate as to the place of origin of similar pictorial pottery, with the focus on the Aegean area or Cyprus. It was also suggested that the krater was the work of a specific painter whose work was found in Tell el-Ajjul (Israel), Maroni (Cyprus), Miletos (Turkey), Lalyos (Rhodes) and Berbati, Mycenae (Greek mainland). INAA of the Tel Dan krater placed the origin in the Argolid (Yellin and Maeir 1992).

INAA is a most powerful tool in relating obsidian artifacts to their geological sources. Such studies have thrown light on ancient trade and exchange networks in the Near East (Perlman and Yellin 1980), the Americas (Glascok, Speakman, and Neff 2007), and elsewhere.

Gemstones, such as turquoise and jade, have been analyzed by INAA (Weigand, Harbottle, and Sayre 1977; Bishop, Sayre, and van Zelst 1983), as well as precious metals (gold, silver). However, relating precious metals to their sources by INAA is very problematic as precious metals are reworked, melted and mixed, and therefore lose their geochemical signature of their origins.

INAA has been applied to limestone and marble with varying degrees of success. Trace element concentrations in these materials are very low and often at the detection limit. However, multivariate statistical methods applied to limestone compositions have made it possible

to identify common sources, and in this way reconstruct limestone sculpture from fragments in widely different locations with significant benefits for art history (Holmes, Little, and Sayre 1986).

Basalt, flint, and pumice are all amenable to analysis by INAA, as is faience and glass.

SEE ALSO: Characterization of Ceramics; Chert, Silex, and Obsidian Sourcing; Compositional Data Analysis; Elemental Analysis of Pottery; Neutron Activation Analysis (NAA)

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Ink

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The portability, potency, and lasting permanence of ink have made it a preferred communication, therapeutic, and punitive device by cultures around the world since its invention in antiquity. In Neolithic Europe, ink derived from soot is known archaeologically as a substance used in therapeutic tattooing practices dating to the third millennium BCE (Deter-Wolf et al. 2016). In ancient China and Egypt, a legacy of ink production exists for writing, painting, and tattooing, which allowed secular and religious information to be shared across time and space.

Several contemporary scholars attest that Chinese philosopher Tien-Lcheu (also Tien Chen) invented writing ink in 2697 BCE, but ancient texts do not record the event and this modern construction is contradictory to known historical facts (Laufer 1926, 4). Notwithstanding, historians believe that ink was simultaneously invented in Egypt and China between 3000 and 2500 BCE. The earliest Chinese inks were manufactured from pine soot mixed with a thickening agent, such as animal skin gelatin. Han Dynasty (206 BCE–220 CE) records describe the usage of ink pellets, balls, ink cakes or inksticks, which allowed for easier transport, handling, counting, or consumption when utilized as a medicine (Laufer 1926, 22–23). Much later, during the Northern Song Dynasty (960–1127 CE) are documented recipes for oil soot ink, but recent archaeological discoveries from the Astana necropolis indicate that ceramic lamps dated to the first half of the seventh century CE contain the earliest samples of oil soot ink stock, perhaps for use in local tomb paintings (Shevchenko et al. 2017). Ink was also used very early in Chinese history to mark criminals. The *History of the Former Han Dynasty*, completed in 111 CE, describes 500 crimes punishable by tattoo during the Zhou Dynasty (1046–256 BCE).

Black ink suitable for writing was introduced to Tibet from Indic sources in the seventh century BCE. However, many ancient Tibetan books were written with colored inks derived from mineral sources, like gold, silver, cinnabar, and vermillion. These colors were associated with specific religious virtues and characteristics: Gold is for wonder, wealth, and opulence; red is for alarm, power, and resolve to control one's personal capacities and command of knowledge and wisdom, and so on (Helman-Ważny 2014). Tibetan writing inks were usually contained and transported in brass ink pots. In neighboring India, where the earliest deciphered epigraphic inscriptions date to the fifth to third centuries BCE, ceramic ink pots dating to the first century CE have been recovered archaeologically.

Tamgas, or animal brands and property marks that evolved into dynastic signs and emblems, appeared among early nomadic Eurasian cultures (Sarmatians, Massagetae, Alans) more than 2,000 years ago. One of the earliest tamgas, a square jade ink stamp, dates to the Warring States Period in China (475–221 BCE) and was used by Xiongnu rulers as a seal of office (Tezcan 2010, 384). Among the Mongols, the tamga was originally associated with a tribe or clan, but it later evolved into a seal of state, legitimating the empire as one of law and order. During the Il-khanate period (1256–1350 CE), several ink colors were used with tamgas to indicate the status of the owner. Use of the wrong color was punishable by death. The Nenets of Siberia applied tamga tattoos to their bodies, but these practices ceased in the twentieth century (Rudenko 1929, 16).

The first Egyptian writing inks were created by burning organic materials to form soot mixed with a binder, such as Acacia tree gum, which kept the carbon particles from settling and served to fasten them to paper. The nonfading slurry was used on papyrus paper, of which the first examples containing text are preserved in administrative documents dating to Dynasty 4 (ca. 2500 BCE) (Capua 2015). Early black ink scripts have also been found on ancient ostraca, pottery shards, or limestone flakes, in Egypt and throughout

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the Fertile Crescent. Another predominant color seen on early papyrus, tomb walls, and objects of material culture is “Egyptian blue,” the first artificially made pigment, produced by heating quartz sand, copper, burnt lime, and an alkali like natron. Scanning electron microscopy/energy dispersive X-ray spectrometry studies have identified the earliest documented use of this pigmented ink, which occurs on a Dynasty 0 (3250 BCE) alabaster bowl incised with hieroglyphs filled with the blue frit (Corcoran 2016). Red inks derived from hematite also appear on early Egyptian papyri. The color was used in titles and headings to distinguish them from other hieroglyphic text.

Tattooing inks, presumably from soot, also mark the bodies of ancient Egyptian mummies. New observations using infrared photographic imaging extend the temporal range of known examples to the Pre-Dynastic, including a male and female mummy from Gebelein that possess figural tattoos. Accelerator mass spectrometry (AMS) radiocarbon testing has dated both of these bodies to 3349–3018 cal BCE, roughly contemporaneous with the Neolithic “Iceman” of Europe (Friedman 2017).

Over time, writing ink and the use of papyri spread from Egypt throughout the ancient Mediterranean, since writing on paper was of fundamental importance to recording historical, philosophical, economic, and governmental information. The Roman author and philosopher Pliny the Elder (23–79 CE) carefully described the carbon-based ink utilized in his time. But recent 3D phase contrast tomography has revealed that Greco-Roman papyri from Herculaneum preserved during the eruption of Mount Vesuvius in 79 CE contained metallic ink partially composed of lead, which previous studies had identified as being introduced only in the fourth century CE (Brun et al. 2016). Colored inks were also employed in Roman times, usually by the elite. For example, fifth-century CE Roman law mandated that only emperors could write with highly prized purple ink manufactured from charred marine molluscs in the family Muricidae. Anyone who obtained and attempted to use this expensive colored ink faced the death penalty.

Punitive tattooing with ink (*stigmatias*, “marked slave”) was also commonplace in the Greco-Roman world, and perhaps the first

reference to this form of disfigurement was recorded in a sixth-century BCE poem fragment by Asius of Samos. Other sources document this procedure among the Persians and Romans, with the practice continuing into the late ninth century CE of the Byzantine period. Interestingly, as early as the fourth century BCE, references to tattoo removal appear, with the most descriptive account provided by the sixth-century CE Roman doctor Aetius, who also notes the methods and substances used for applying punitive tattoos.

Across the indigenous world, tattooing inks have been produced for millennia. Numerous recipes were utilized and many were believed to possess magical properties that were passed on to the tattoo client. Perhaps the oldest archaeological evidence for tattooing in North America is a 3,500-year-old Paleo-Eskimo ivory maskette from Devon Island, Nunavut. This naturalistically carved female face displays numerous linear tattoos that were similarly worn among Canadian Inuit women until recently (Krutak 2014). Across the millennia, tattooing ink in the Arctic was quite uniform in composition, consisting of lampblack, lubricating seal oil, and human urine which reduced suppuration. Magical referents were attached to the sooty liquid, which was believed to repel evil spirits and the sicknesses they bring.

For more than 1,000 years, across Indochina, tattoo masters (*ajarn*, *khru sak*, Thai) employed magical inks in a very complex and elaborate system of body marking. Many of the inks are personal recipes believed to possess special protective qualities due to their unusual ingredients. For example, some *ajarns* in Thailand, who are often Buddhist monks, use charred and ground sandalwood steeped in herbs or white sesame oil to impart protection. Liquids extracted from wild animals, such as the bile of tigers and bears, and even cobra venom, are mixed with ink for empowerment. The exfoliated skin of a revered *ajarn* monk added to ink mixed with holy water is thought to imbue the tattooed with qualities that engender reverence and respect in the people they interact with (Krutak 2012, 14).

Contemporary studies of ancient ink are revealing profound insights into the technology and socio-historical contexts concerning its production and usage. At the same time, however, advances in scientific research have demonstrated

novel ways to incorporate this time-worn material into modern technological applications, while also providing new insights into ink conservation best practices. For example, it has been found that Egyptian blue emits near-infrared rays when irradiated with visible light, suggesting a variety of modern applications in telecommunications (e.g., a substitute for infrared beams), printing, and biomedical imaging as a nano-ink. Through use of nondestructive investigative techniques like micro Raman spectroscopy, X-ray fluorescence spectroscopy, and infrared photography, it has become easier to authenticate and stabilize manuscripts by identifying the chemical and structural properties of ancient inks. “Fingerprinting” these ancient inks also enables researchers to map their characteristic traits along chronological and geographic axes, which is exceedingly important since many ancient manuscripts lack a recorded archaeological context or provenance (Ryholt 2016).

SEE ALSO: Conservation; Marine Molluscs; Mass Spectrometry (MS); Photoluminescence of Egyptian Blue; Pigments and Binders; Raman Spectroscopy; X-Ray Fluorescence Spectrometry (XRF); X-Ray Tomography

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Instrumental Analysis of Lithics

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Archaeologists employ a variety of scientific instruments to study lithic raw materials, including stones that were used to make flaked and ground stone tools. This research is primarily focused on the identification of source locations for raw materials. Researchers have employed diachronic and synchronic patterns of source utilization to study such things as trade relationships, territories for migrant populations, inter-regional contacts including migration, common routes of travel, ritually important items, patterns of social interaction, the value or quality of items, and other aspects of human behavior. However, in order to reliably pinpoint raw material source areas it is first necessary to prove the provenance postulate, and sourcing studies are only possible if the compositional variation between sources exceeds differences within raw material outcrops.

Provenance postulate

Locating a raw material source for any artifact depends on identifying one or more physical or chemical characteristics that are unique among possible source areas. The identification of distinctive variables can be difficult due to a number of factors, such as the dispersion of compositionally similar materials across extensive areas. Alternatively, materials may only outcrop within small areas, but they may be compositionally heterogeneous and therefore difficult to reliably differentiate. Thus, a prerequisite of any instrumental sourcing study is the evaluation of the

provenance postulate for the material of interest. This postulate states that artifact sourcing analyses are only feasible if the compositional variation among source areas exceeds, in some recognizable way, the differences within each of them (Weigand, Harbottle, and Sayre 1977, 24).

Evaluation of the provenance postulate requires identifying potential sources of raw materials and then sufficiently sampling them. Geological maps and studies produced by geologists that report outcrops of formations that include the stone type of interest are one of the primary resources that archaeologists employ to identify possible source locations. While some geochemical data may be available from previous geological studies, it is often necessary to visit potential source areas and collect samples for analysis. There is no set standard for sampling source areas, as sample size and scope are dependent on the material's natural distribution and compositional variability, as well as cultural factors including distribution and consumption patterns. For example, obsidian provenance analyses can be conducted using as few as ten specimens from each individual geological source area because the chemical composition of glass is highly homogenous (Shackley 2005). In contrast, studies of compositionally heterogeneous materials such as basalt, chert, ocher and turquoise require many more samples to assess both within and between source compositional variability. Because of these factors, both archaeological and geochemical patterning must be considered when determining sufficient sample sizes for assessing the provenance postulate.

There is no single ideal analytical instrument for investigating the provenance postulate, and the choice of approach depends on multiple factors. First, some analytical techniques are more expensive and/or not as widely available (e.g., thermal ionization mass spectrometry (TIMS)). Second, compositional variation among source areas may be mineralogical, chemical, or isotopic in nature and this affects the choice of approach. Third, different instruments are variably sensitive to lithic constituents. For instance, instrumental

neutron activation analysis (INAA) can reliably detect parts-per-billion (ppb) quantities for some elements. However, it is not as reliable as energy dispersive X-ray fluorescence (ED-XRF) for identifying parts-per-million (ppm) concentrations among the trace elements that are most commonly used for lithic provenance analyses (i.e., Rb, Sr, Y, Zr, and Nb). These five rare earth elements are referred to as “fingerprint” constituents because although they occur in low concentrations, they are commonly present in igneous stones and their prevalence generally varies among individual outcrops (Shackley 2005). A related issue is that some techniques are incapable of identifying constituents that are common in lithic raw materials. For example, silicon dioxide is one of the most abundant compounds that comprise the rocks on the surface of the earth, but ED-XRF is incapable of identifying oxygen and only has limited sensitivity for silicon. Consequently, multiple analytical instruments may be necessary to fully identify and understand compositional variation among lithic source areas. Because of these issues, it is essential that archaeologists thoroughly review the various analytical techniques that are available before selecting an approach.

Sample preparation and treatment are also important considerations when selecting an instrumental technique. Some analyses can only be completed through the destruction of the artifact prior to or during analyses, whereas other approaches can be undertaken with no permanent damage to archaeological remains. For example, ED-XRF can be conducted with or without damage to the sample. For homogeneous materials such as obsidian it is possible to collect ED-XRF data from unmodified archaeological samples without damaging them in any way. However, in order to calculate elemental concentrations for heterogeneous materials or items of unknown composition, it is necessary to reduce the sample to a fine powder and then further homogenize it by compacting into a pellet and/or vitrifying it. While it is generally possible to conduct destructive analysis of natural stone from geological outcrops, ethical and legal issues may limit any analyses that cause damage to the archaeological materials. Consequently, archaeologists may not be able to employ some techniques that work well for geological sourcing, and these

source geochemical data may be of little use if it is impossible to collect similar information from cultural remains.

A final consideration is that some analytical techniques can only be completed in a laboratory (e.g., INAA, scanning electron microscopy (SEM), and laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS)), while portable instruments are available for some types of analysis including XRF. The fully portable nature of ED-XRF instruments allows applications for archaeological materials that would be otherwise impossible. Examples of such applications include the analysis of pictographs, and the collection of compositional data for in-situ architectural stones or other undisturbed archaeological remains. The comparatively low cost and widespread availability of ED-XRF devices, combined with the potentially nondestructive and fully portable nature of the analysis has led to the recent widespread application of ED-XRF to archaeological lithic studies. In some cases, however, other instruments may be better suited to prove the provenance postulate for a given raw material, and researchers should study and understand the strengths and weaknesses of different instrumental analytical techniques.

Archaeological research issues

Much of the archaeological research on lithic source locations has been directed toward questions associated with settlement strategies, especially the degree of sedentism. For example, “some researchers believe that non-local raw materials are more likely to be found on shorter duration sites than on longer duration sites” (Andrefsky 1998, 219–20), and lithic raw material diversity is similarly suggested to be associated with occupation length. Colin Renfrew (1977, 72–78) suggested the “law of monotonic decrement” to describe the negative correlation he observed between distance from the source and the quantity of material, and lithic researchers generally expect that stone abundance should decrease with distance from the source. In addition to decreasing in quantity, studies have demonstrated a relationship between source

distance and cortex percentages on artifacts, and a general tendency for greater reduction of stone from distant locations (Odell 2003, 196). Some researchers have used perceived distance decay relationship deviations to infer territorial areas for mobile groups. For example, Goodyear (1989) observed that many Paleo-Indian sites in North America have substantial quantities of nonlocal lithic material from up to 200 km away, and he argued that the distance to these sources indicated the size of the band territory. Variations from expected distance relationships are also sometimes argued to indicate that a raw material had a special ritual or social significance (Kooyman 2000, 147).

For many reasons, lithic source analysis literature has focused on research issues associated with mobile hunter-gatherers, and in situations where a fully sedentary settlement pattern is apparent or assumed, archaeologists often assert that raw materials from distant sources (e.g., those further than a day's travel) arrived at sites as the result of trade relationships. In order to demonstrate that trade or exchange occurred, however, researchers must address three primary issues (Odell 2003, 209). First, it is necessary to reliably establish the source of raw materials. Second, the manufacturing location for the product must be identified. Third, the mechanism for material displacement needs to be established. While analyses of the first two factors have often produced widely agreed-upon results, demonstrating the third aspect has proven more difficult and controversial. For example, some researchers have argued that the presence of unworked exotic raw materials indicates that direct access existed to source areas, whereas finished goods of non-local materials at a site that lacks manufacturing debris are taken as evidence for trade. While the latter may be possible evidence for trade, the former does not necessarily indicate direct access to source locations, because raw materials as well as finished products can be exchanged (Loendorf, Fertelmes, and Lewis 2013).

Although examination of distance decay relationships is employed to suggest different mechanisms for material transport, analytical problems exist when comparing archaeological data with hypothetical distance relationships. Some major issues include the following. First, this approach requires data from many sites,

but archaeologists rarely have information from contemporaneous components that are also spread uniformly across the landscape at evenly varying distances from a given source. More often, data from just a few or even one site are available, site data may cluster in groups at similar distances, and/or sites at varying distances are from different time periods. Second, different raw material acquisition mechanisms are not necessarily mutually exclusive, and multiple approaches may have been taken even at a given moment in time. Third, the slopes of distance decay correlation lines are related to many variables, including such things as transport costs (i.e., transporting goods over land versus water, or with human porters versus pack animals), in addition to the nature of trade or exchange interactions. Another factor demonstrated by Brantingham's (2003) simulation of lithic raw material acquisition is the effect of raw material density and distribution in the environment on both material diversity at sites and distance decay relationships. Despite these limitations, examination of the relationship between material quantities and distance to the source provides useful information regarding the movement of goods on the landscape.

Sourced lithic types

One common application for instrumental analysis is the identification of source locations for flaked-stone raw materials, especially obsidian. Obsidian is readily sourced using fully portable ED-XRF devices, and it can even be conducted on noncollection archaeological survey projects. Basalt, including fine-grained and vesicular varieties, has also been successfully sourced in different regions using ED-XRF. Because of their compositional heterogeneity, it is difficult or impossible to prove the provenance postulate for most chert (i.e., flint or jasper) and chalcedony (i.e., agate) varieties, though some researchers have had success separating macroscopically similar varieties of these materials by examining fluorescence patterns under ultraviolet light.

Other types of lithic raw materials that archaeologists have attempted to identify source

locations for include stones that were predominantly employed to manufacture ornaments and were commonly transported across comparatively long distances, including materials such as turquoise, chrysocolla, jet, steatite, and argillite. For example, multiple analyses undertaken in the past half-century have attempted to identify consistent compositional variation among the turquoise deposits in the greater southwestern United States (Weigand et al. 1977, 24). However, researchers have identified a number of logistical and analytical obstacles, including several key issues: (1) biased sample selection of archaeological turquoise; (2) intrasource compositional variability of turquoise varieties; (3) an insufficient understanding of intersource compositional variability; and (4) lack of adequate source sampling in some regions.

Archaeologists have also used instrumental analyses in an attempt to identify source locations for lithic pigments that predominantly consist of softer stones, such as ocher, malachite, azurite, and limonite. One of the main applications for pigment identifications and sourcing has been in rock art research. Pictographs were created using a variety of naturally occurring pigments including ocher (to produce purple, brown, red, or yellow), charcoal (for black), and kaolinite (to produce white). Ochres are among the earliest pigments used by humankind. They are derived from naturally tinted sediments that contain iron-bearing minerals. Mineralogically, ochers are generally intermixed with other minerals such as quartz, clays, gypsum, or mica. In addition, ancient potters may have intentionally added materials to ocher to act as binding agents that served to facilitate and prolong the fastening of paint to stone surfaces, and/or as extending agents to reduce the amount of pigment that was required. Therefore, the chemical composition of pigments may be unique in both space and time, making it theoretically possible to distinguish among different ocher sources and/or different paint recipes using instrumental analysis.

SEE ALSO: Characterization of Pigments; Chert, Silex, and Obsidian Sourcing; Gemstones; INAA and Material Analysis; Ion Beam Analysis (PIXE/RBS); Isotopes; Lithics Data Quantification; Neutron Activation Analysis

(NAA); PIXE and Material Analysis; Portable X-Ray Fluorescence Spectrometry (pXRF); X-Ray Fluorescence Spectrometry (XRF); XRD and Materials Analysis

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Magnetic Tapes

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Audio and video records on magnetic tapes form an essential part of twentieth-century cultural heritage, representing the memory and identity of societies in the diversity of world perspectives. The conservation of magnetic tapes is a global challenge with a tight timeline. Presto (2001) found (in a study covering 4 million hours of content) that 70 percent of audio, video, and film contents are at immediate risk from obsolescence of formats and equipment, tape decay, and damage to carriers. Considerable volumes of records, estimated at 200 million hours, are at stake and will need to be digitized within the next 15–20 years or be lost irreversibly.

A major risk facing magnetic tapes is the general lack of awareness among collection stewards, resulting from the fact that their deterioration is not easily apparent. Global disparity further aggravates the “digital divide” between North and South, compromising equal access to the collective memories of the world. Increased efforts to build better physical infrastructure for the storage of sound collections at low temperature and humidity conditions are critical (Library of Congress 2012).

In the discussion about value and significance in magnetic tape conservation, the content is given priority over the original, tangible representation of the object. However, there are also specific aspects that need to be considered when the handling of the original is discussed.

Analog audio and video recordings on magnetic tapes need to be digitized; content from digital carriers needs to be moved into files by digital to digital transfer. A major challenge of this process is to manage the quality through cycles of encoding, decoding, and reformatting and to preserve the connected metadata.

In order to ensure sustainability, new technical solutions for long-term preservation and access

will require considerable human and financial resources, as their needs are different from traditional library and archive materials.

Digital audio files are today's accepted format for analog recordings. By their nature, their preservation needs active management, including data migration and solving obsolescence issues, including the development of new technologies. “Preservation is the totality of the steps necessary to ensure the permanent accessibility—forever—of an audiovisual document with the maximum integrity” (Edmondson 2004, 20). The concept of “maximum integrity” is reflecting the current ethics in conservation and means that the new master should contain as much of the quality of the original as is technically feasible. Each new recopying of a magnetic tape, video, or audio generates a loss in signal, with video tapes being more problematic than audio tapes, due to their existence in a wider breadth of incompatible and short-lived versions.

While this entry focuses on magnetic tapes, it is important to note that tape recording technology actually is based on two independent components—tape and recorder, both susceptible to decay, and each with specific preservation challenges.

History of magnetic tapes

After magnetic recording of sound was demonstrated in 1898 by Valdemar Poulsen, the German–Austrian engineer Fritz Pfleumer (1881–1945) was granted in 1928 a patent for using thin paper coated with lacquer-bound iron oxide powder for sound recording.

Based on Pfleumer's research, AEG Telefunken (Berlin) developed in 1935 the “Magnetophon,” a recorder that used a carrier of cellulose acetate foil, coated with a lacquer of cellulose acetate-bound iron oxide. Magnetic tapes came into wider use in the 1940s after the development of electrical amplification and improvements in fidelity. From the mid-1950s onward, home audio recorders were developed, and in the 1960s cassette formats appeared on the market.



Figure 1 Recording a Fourier transform infrared spectroscopy (FTIR) spectrum in ATR technique for a magnetic tape.

Source: © Rathgen-Forschungslabor, Staatliche Museen zu Berlin.

The technology has been widely used and adopted as the reference, with no major modifications for decades except for the materials used. The twentieth century saw a rapid succession of formats being first developed and then quickly abandoned, an impressive chapter in the history of polymers in conservation.

Magnetic tape is also the oldest memory medium for computers, used for the first time to record data in 1951 in the Mauchly-Eckert UNIVAC I computer. From the mid-1950s onward, magnetic tape was also used for video recording.

Today, the early recordings on wire, steel ribbons, paper, or cellulose acetate tapes with low coercivity constitute only a very small part of the audio/visual archive collections. Practically all audio-specific magnetic tape formats are today out of use, as audio recording and storage became part of the digital world with its specific formats.

Composition of magnetic tapes

Magnetic tapes consist of three components: magnetic particles and binder, combined in the magnetic layer, capable of “storing” the

sound by magnetism impressed on them by the recording head, and a base film/backing, which provides structural support. All three components can be individual sources of decay and failure (Schüller 2008). Microscopy and scanning electron microscopy with energy dispersive spectroscopy (SEM-EDS) material analysis of cross-sections clearly reveals the layered structure of the tapes.

Spectroscopy, specifically attenuated total reflection (ATR) infrared absorption spectroscopy, provides a powerful tool for analysis of the base film and magnetic layer (Gómez-Sánchez, Kunz, and Simon 2012). The low penetration depth of ATR ensures that both sides can be analyzed independently (Figure 1).

Base film/backing materials

In the sequence of the development of magnetic tapes, paper, cellulose acetate, polyvinyl chloride, and polyester (polyethylene-terephthalate) were used. Cellulose acetate has been in use for backing from the “Magnetophon” onwards until the 1960s and 1970s. Adapted from the film industry, it replaced unstable cellulose nitrate

films as so-called safety film. While many tapes recorded at the “Reichsrundfunkgesellschaft” are still playable today, cellulose acetate may over time become brittle and shrink. This deterioration process is highly dependent on storage conditions. High humidity and temperature levels further add to deterioration, and inadequate mechanical handling is another damage factor.

Polyvinyl chloride tapes, produced mainly in Germany between 1944 and 1972, are not known to experience significant chemical deterioration. Polyester, which has gradually replaced cellulose acetate and polyvinyl chloride backing from the late 1950s onward, is mechanically and chemically also quite stable.

Magnetic layer

The first widespread magnetic pigment used was ferric oxide ($\gamma\text{-Fe}_2\text{O}_3$) which was used for all open reel audio tapes, compact cassettes, and the first video formats. It is chemically stable. In comparison with iron oxide pigments, chromium dioxide (CrO_2), and metal particulate (MP) pigments such as barium ferrite particles, provide a higher tape signal output and permit higher recording frequencies, but are more prone to decay.

Pigment binders

The binder is used to bind particles within the magnetic layer onto the backing. Higher magnetic particle density requires lower binder quantity but sufficient binding properties. Many tapes from the 1950s and 1960s have polyvinyl chloride binders.

The majority of tapes from the 1970s onward use polyester-polyurethane and poly(ether-urethanes). Also, copolymers of vinylchloride, vinylacetate, and vinylalcohol, and copolymers of vinylchloride and acrylonitrile have been reported as binders.

Finally, certain additives are added to the binder: lubricants for reducing friction, tension, and tape wear; a head-cleaning agent to limit the formation of head clogs; and carbon black to reduce static charges, which could cause soiling of the tape.

Deterioration processes

Deterioration of magnetic tape occurs in the base film and/or the magnetic layer—within the binder or the magnetic particles. If the binder loses integrity (through softening, embrittlement, loss of cohesiveness, or loss of lubrication) the tape may become unplayable.

The best-described damage processes are those affecting either the base film or the binding media, among them “*sticky shed syndrome*” of the magnetic layer, often attributed to binder hydrolysis, and base material degradation like “*vinegar syndrome*.”

Cellulose acetate tapes become brittle with age and are subject to curling and distortion. Additionally, they can show “vinegar syndrome,” caused by hydrolysis and deacetylation of the polymer. Since the free acetic acid released acts as a catalyst, it is important to reduce the amount of free acetic acid in the environment of the material. There is no linear relationship between physical properties such as tensile strength and the degree of deacetylation.

Affecting mainly modern polyester-polyurethane tapes, “sticky shed syndrome” is a commonly used term to describe the phenomenon associated with deterioration of the magnetic layer (De Lande 1990). The condition causes squealing during playback and deposition of a sticky material on playback heads. This can lead to a significant loss of high frequencies (audio) or a complete breakdown of the signal (video), sometimes leading to collapse of the binder and the complete loss of information.

Problems with sticky tapes generally occur within a few years after production. Not so frequently, tapes become sticky at later stages of their storage, except where they were stored under conditions of high humidity. Not in all cases, hydrolysis of polyurethane (PU) has been made responsible for “sticky shed syndrome,” and a number of other reasons have been discussed as well: One was the exudation of the primer, the often PVC-based binding layer between backing and magnetic layer, or the back coating, respectively. Another one could be the dispersing agents applied to ensure a proper dispersion of the particles within the magnetic layer. Also, lubricants in some tapes, often stearic or oleic acid, which are used to minimize friction, sometimes show

a tendency to be exuded. Because of the higher head-to-tape speeds, video tapes contain more lubricants than audio tapes.

Generally, the playability problems vary significantly between manufacturers and seem to be directly related to the chemical breakdown of the tape binder layer. Next to infrared spectroscopy, gas chromatography–mass spectrometry (GC-MS) is a useful tool to study the causes of tape decay.

Damage in tapes caused by binder hydrolysis are reflected also by a modification of the surface topography. As revealed by confocal microscopy, the mean roughness depth increases with the degree of degradation (Gómez-Sánchez et al. 2011). Due to various chemical formulations and deterioration mechanisms, good markers for condition assessment are related to the tribological behavior of tapes. These markers are surface (surface tension, surface acidity) and mechanical (friction, durability) properties (Prestospace 2006).

Finally, also biodegradation, specifically mold, can affect and damage magnetic tapes. This occurs at relative humidities (RH) of 70 percent and higher.

Preservation strategy

The level of risk for a tape to be lost will depend on its specific vulnerability, its susceptibility to chemical decay, the storage conditions, the quality and availability of replay equipment, and the professional skills of the operators. Archivists often are learning that their professional training has not prepared them sufficiently for dealing with recording media and systems, lack of awareness being a huge risk factor. The small size of many archives with a correspondingly low digitization rate is another issue.

The migration to digital repositories is both expensive and time-consuming. It is important to develop a strategy that takes the individual situation of the collection into account. According to the “Ethics, Principles and Preservation Strategy” established by the International Association of Sound and Audiovisual Archives (IASA 2005) for the safeguarding of audio heritage, priority should be given to those documents that are:

- at immediate risk; and/or
- part of a commercially unsupported system; and/or
- in regular demand.

A good preservation strategy based on conservation triage therefore involves:

- examining the collection, identifying types of tapes, and setting priorities based on their stability;
- understanding the preservation rerecording and how it works, including the transfer technology and migration options across the various media.

A long-term conservation strategy comprises at least three dimensions:

- preservation of the original carrier;
- rerecording of a 1:1 preservation copy;
- creation of an access copy.

Recommended environmental conditions for preservation storage for audio tapes are: 25–30 percent RH $\pm$ 5 percent; 8–10 °C $\pm$ 1 °C; video should be stored separately at slightly higher conditions (18 °C, 35% RH), with secured air circulation. Tapes affected by “vinegar syndrome” should be isolated from the rest of the collection due to catalytic function of free acetic acid on the hydrolysis of cellulose acetate.

Preferable conditions of access storage are closer to the ambient conditions of use: 40 percent RH $\pm$ 5 percent, approximately 20 °C $\pm$ 3 °C. Recent concepts based on the green museum debate advocate for broader margins of humidity ($\pm$ 10 percent) and temperature fluctuations.

In the case of “sticky shed syndrome,” De Lande (1990) recommended as a temporary solution to heat (or bake) the tape at a low temperature for several hours until the oxide readheres, and then copying the recording to a fresh tape. Two alternative methods, the temperature-controlled oven and the microwave oven, are equally useful, 50–60 °C being a sufficiently high temperature, well below the Curie temperature of the magnetic pigments.

The difficulties of transferring video are perhaps even more complex, as most of the video formats had shorter lifetimes and are now antiquated. It is increasingly difficult to

find machines that can play certain formats for migration purposes.

It is also important to create a detailed inventory of the collections, record the physical condition of the material, and define the value and importance of the collection and its contents. Conservation documentation is a key element in this process.

SEE ALSO: Conservation; Conservation Documentation; Conservation Science; Gas Chromatography–Mass Spectrometry (GC-MS); Heritage and Sustainability; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Optical Microscopy; Polymers in Conservation; Value or Significance

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Metallography and Crystallographic Texture Analysis

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Introduction

Archaeological materials are invaluable to the study of past societies (Pollard and Heron 2008). In addition to the anthropological information provided, an archaeological artifact is capable of revealing the technology used in its making. Use of analytical techniques may help archaeologists to determine the origin of materials used and trade routes, and even if a technology is local or imported.

Metal artifacts sometimes require the use of techniques from different branches of science for their study and preservation. The study of metal artifacts can be carried out by applying relatively simple or more complex methods; for example, the composition of the material can be determined by means of X-ray fluorescence (XRF) or energy dispersive spectroscopy (EDS). With optical microscopy, it is possible to determine the microstructure of the object, hinting at its production process. In addition, corrosion mechanisms must be taken into account for preservation.

One of the major advances in the study of metals and alloys was the discovery that their microstructure was the result of their processing history (Holloway and Vaidyanathan 2010). Even if nondestructive characterization of metals is now possible, from an analytical point of view, whenever possible, it is best to remove a small sample of the metal object and cut, polish, and mount it on resins for analysis. In addition to microscopic examination, this procedure allows further physical examination of the sample. It is

possible, for example, to study the physical evidence left by thermal and mechanical treatments that the metallic alloys were exposed to and determine ancient technological processes (Pollard and Bray 2014).

Archaeometallurgists have been using the metallographic microscope to study compositional phases and structural features that reveal the annealing and work-hardening of metal production in antiquity. Although optical microscopy is a great tool to study metal structure, recent use of scanning electron microscopy (SEM) provides higher magnification and punctual chemical analysis of the present phases (Rapp 2000).

The use of X-rays makes it possible to identify features not easily visible due to corrosion. With X-ray diffraction (XRD) it is possible to determine the grain orientation (crystallographic texture) and crystalline phases present in the metal. With other optical instruments and principles, it is possible to explore what is known as the microstructure of metals and alloys and to observe the phases that compose them, including transformations that they have undergone during their processing and use. In addition, it is possible to gather information about the preservation or deterioration process over time.

With development of instruments currently available in the field of metallography and crystallography, it is possible to obtain information on chemical composition, crystallographic characteristics, and other properties, such as a metallic material's morphology, roughness, surface topography, imperfections, inclusions, and slags.

Metallographic techniques

Metallography consists of the observation of a piece by means of a metallographic optical microscope or scanning electron microscope in order to determine the type and morphology of the microconstituents of the material (Scott 1991). This is of utmost importance and is related to material properties; the proportions in which they are present, for example, reflect the

mechanical, thermal, and chemical deterioration to which the material has been subjected. To carry out this analysis, preliminary preparation steps are required which can be synthesized in the selection and extraction of the samples, their assembly (if required), coarse and fine sanding, and final polishing—leading to a specular appearance on the surface and a chemical etching. With this it is possible to reveal the microstructure, achieving a maximum magnification of the order of 1,000 X.

Metallography can provide valuable information about archaeological metal objects. In the case of ferrous parts, the most outstanding aspects are:

- The presence of slag inclusions, whose volume and shape may provide elements for determining the manufacturing process.
- Identification of the type of alloy and the different phases present.
- Phases that result from the use of heat treatments, for example acicular structures, associated with quenching and tempering, or spherical structures as evidence of materials that were cold-worked and then annealed.
- Evidence of composite parts, generated by joining processes such as welding, for example in sharp tools.
- It has sometimes been possible to detect the presence of carburized zones. Regarding both ferrous and nonferrous alloys, the presence of various phases in the alloys can be highlighted.
- Determination of mechanical forming processes, such as cold-working (through the presence of elongated grains) or cold-working plus annealing (through the presence of equiaxed grains).
- Evidence of casting processes, observing a predominant dendritic microstructure in the material.

With SEM, information obtained with the metallographic microscope can be deepened and expanded. In the case of electron microscopy, an electron beam is used, which, when interacting with the material, produces various radiations through which images can be obtained and the

ordering or information of the chemical composition of the parts detected. Depending on the thickness of the samples and intensity of the electron beam, information can be generated at the surface level and a few micrometers below it (SEM), allowing detailed observation of the surface topography of objects, careful study of the impurities and inclusions of the material, and determination of the chemical elements that in a precise way are required to explain aspects of the manufacturing and metallurgical history of the objects. X-ray radiation can be emitted, the resulting pattern being specific and characteristic of each chemical element. Thus, it is possible to determine—through either EDS or modification of the wavelength (wavelength dispersive spectroscopy (WDS)—the elementary qualitative and semiquantitative composition of the samples.

Crystallographic texture analysis

A basic aspect of common metallic materials formed by grains or crystals is that mechanical properties depend on the orientation of each of these; this is called crystallographic texture. There are three experimental ways to determine texture: (1) XRD, (2) electron diffraction, and, more recently, (3) neutron powder diffraction. The first method can evaluate a relatively large area of the sample (several grains) so that the information obtained is representative of the material. In the second technique, the evaluation is made grain by grain, which allows for greater detail in the study of the texture of the material.

Determination of different textures in a material is useful for knowing their behavior against mechanical loads. The results of XRD, electron diffraction, and neutron powder diffraction can be reflected in pole figures and through the use of orientation distribution functions (ODF), with which it is possible to construct predictive models of the mechanical and microstructural properties of a material (Artoli 2007).

Hardness and microhardness

The hardness test is a very useful tool for the characterization of materials. Hardness values of an empirical nature can be correlated with other mechanical properties such as tensile strength. There are several types of tests, all based on the resistance of the material to penetration by an indenter when a load is applied.

Hardness tests have a relevant field of application when there is sufficient quantity of material (which often does not occur with archaeological material) and with mechanical properties that allow the use of larger loads. They provide a tool, through the evaluation of a general indentation, to obtain a general hardness value of a material, and with that vision they should be applied, because if the sample preparation process is simple, the degree of sensitivity will be lower than that of other types of hardness tests. Microhardness tests (the most common variants being Vickers and Knoop) employ smaller loads than those used in hardness tests; using smaller amounts of material (so that they can be adapted to the conditions of the archaeological material available), it is possible to obtain information on components that can evaluate different sections of a sample.

Sample cases

Some cases that illustrate the application of these techniques can be found in the literature. For example, SEM, XRF, EDS, and XRD have been used; through metallographic studies, it was possible to explain how the corrosion deterioration process of copper ingots was developed, which was considered to be related to the techniques by means of which the copper alloys and subsequent processing technologies used were made (Garbacs et al. 2015). Usually, the corrosion resistance of copper and its alloys is good; however, over very long periods of time, under certain conditions, they may undergo degradation processes of an electrochemical nature. Thus, metallographic study allows us to explain the relevance of grain boundaries as sites of greater chemical activity, associated with the possible presence of segregation, impurities, and crystallographic

imperfections within the grain boundaries themselves. Also, with metallographic study it has been possible to determine the type of corrosion linked to the corrosive medium where it occurred. For example, for copper and its alloys, pitting and intergranular corrosion are most common when the medium is seawater, while general corrosion is usually present under atmospheric and soil corrosion conditions. Another related case (Ashkenazi, Iddan, and Tal 2012) in the study of copper objects and their alloys is the evaluation of 14 bronze artifacts from the Hellenistic period that were characterized by optical microscopy, microhardness, SEM, EDS, and XRD. Because of the metallographic study it was possible to determine that the objects had been elaborated by cold-working processes, and even in some objects, evidence of the development of sophisticated Cu-Fe joining methods was found.

In the study of historical objects of ferrous alloys, a first example is that related to iron pieces located in ships that were shipwrecked (Ashkenazi et al. 2012), in which the techniques of X-ray, optical microscopy, SEM-EDS, and XRF, and measurements of microhardness were used. The connection between microstructure and mechanical properties allowed researchers to conjecture about the use of processes such as hammering and/or quenching in ancestral times. This provides archaeologists with evidence about the ancient manufacturing processes and probable uses of the objects studied, and to estimate their antiquity.

SEE ALSO: Deterioration of Metals;
Metallography; Neutron Diffraction (ND)

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Nondestructive Compositional Analysis of Ceramics

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Identification of the manufacturing origin of goods provides archaeologists with insight into the patterns of trade and economic conditions within past societies. This information is vital to identifying sources of supply and demand in ancient times. Similarly, recognition of how goods were produced furnishes an understanding of the technological sophistication of specific cultural groups, allowing archaeologists to discern changes in manufacturing practices over time.

If the source and manufacturing techniques used in the manufacture of pottery can be identified, ceramics, the most frequently recovered artifacts from ancient sites, have the potential to reveal important information about past societies.

The compositional analysis of pottery provides a fingerprint of the material from which it is made, thereby helping to identify the source of the clay and the workshop location. Today, the ceramic specialist uses a wide variety of techniques to determine the composition of the clay from which pottery is made and to identify the technical capabilities of ceramic producers within ancient societies.

Compositional analysis is usually determined by methods such as petrographic analysis using optical microscopy (OM), X-ray fluorescence spectrometry (XRF), inductively coupled plasma mass spectrometry (ICP-MS), inductively coupled plasma atomic emission spectrometry (ICP-AES), and less frequently neutron activation analysis (NAA). Studies of the technology employed in the manufacture of pottery furnish information on the preparation of clay, and forming and firing temperatures, allowing archaeologists to understand the sophistication

of ceramic production in specific societies. Such investigations utilize a number of techniques such as X-ray diffraction (XRD), differential thermal analysis (DTA), scanning electron microscopy energy dispersive X-ray fluorescence (SEM-EDX), thermogravimetric analysis (TGA), and thermal expansion (TE) (Madrid Fernández and Buxeda i Garrigós 2002).

While these methods have each played an important role in determining the manufacturing source of pottery and identifying the technology employed to make ceramics, this knowledge comes at considerable cost because most of these investigative techniques require the partial or total destruction of the ancient material, resulting in the obliteration of large amounts of historical material. While some analytical techniques, such as petrographic analysis, are considered nondestructive because the majority of the sample in question remains intact, they can be at best considered minimally destructive because the samples need to be removed from the original artifact for testing. In addition, some techniques, such as NAA, render the samples radioactive, which means that contemporary access to the ancient material is severely restricted.

Ideally, the removal of a sample for compositional testing should not affect the structural integrity of the vessel, nor should it impact on the visual attributes of the sherd in terms of the diagnosis of its vessel form. Consequently, it is common to take samples from the base or foot rim of the vessel, because assessment of the vessel shape is usually made by analysis of the rim and wall profile. Once removed, these samples cannot be reinstated. This is an irreversible process.

Furthermore, these destructive techniques are either predicated upon the assumption of complete uniformity of composition of an item or the complete destruction of it to be able to prove otherwise. Sampling error therefore becomes a significant, yet routinely ignored consideration.

To overcome these problems, in 2011 John Magnussen and Jaye McKenzie-Clark developed a nondestructive technique using dual energy computed tomography (DECT) to analyze the

composition of archaeological ceramics. This research was undertaken at Macquarie Medical Imaging, Macquarie University, Sydney, Australia (McKenzie-Clark and Magnussen 2014).

Computed tomography (CT)

The technique of CT is complex and it is important to understand the basic principles of the process before discussing DECT. Conventional polychromatic CT scanners, first employed in the 1970s, use a system of a rotating X-ray tube, opposite a concave, curvilinear array of X-ray detectors. Rays are passed through the object of interest and the attenuation or weakening of the rays is measured as a series of projections on the detector on the opposite side of the object. This information is collected at various angles around the object and it is then possible to reconstruct an image that gives a map of the object in terms of the differing X-ray attenuation.

X-ray attenuation is classically expressed as the Hounsfield Unit (HU) density of parts of an object, wherein 0 HU is water, -100 HU is fat, -1,024 HU is gas, and values > 0 HU range from soft tissue to metal. The maximum value typically allowed is +3,072 HU, which normally represents complete beam attenuation. The values reflect the biologically centric nature of the technique and also historical limitations on data storage (-1,024 to +3,072 is a 12-bit range).

The degree to which the X-rays attenuate is directly related to the composition of the object they are passing through. X-ray attenuation is caused predominantly by a combination of the photoelectric effect and Compton scattering. The former is strongly related to the atomic number (Z) of the material of the object, while the latter relates to electron density, which is proportional to mass density (ρ) for most materials. When using a polychromatic X-ray beam it is not possible to separate the contribution from these two effects. This means that a material of higher atomic number but lower density is indistinguishable from one that has a lower atomic number and proportionately higher density. For instance, a pair of objects in which one has a higher atomic number (due to different minerals) but lower density (due to production techniques) can give

identical HU on conventional CT to those of a lower atomic number but higher density.

A further difficulty when analyzing material using CT scanning is that there is preferential attenuation of lower-energy photons when passing through many substances of interest, resulting in an increase in the mean energy of the beam, an effect called beam hardening. This makes analysis of larger objects more difficult because of the gradual loss of X-ray photons in the beam and a combination of less accurate HU density assessment and, in the extreme, photon starvation, when there are insufficient X-rays that pass through parts of an object to be able to effectively reconstruct its internal architecture.

The usefulness of conventional, polychromatic CT for the accurate characterization of pottery samples is therefore limited, beyond simple determination of three-dimensional shape and gross or comparative measurements of any internal features.

Dual energy computed tomography (DECT)

In contrast, DECT uses measurements from two different energy spectra, thereby enabling a basis material decomposition to be performed for each ray path, and providing the relative contribution from each material to the total linear attenuation coefficient along that path. Using reconstruction techniques, the relative contribution throughout an object can then be calculated for each of the basis materials. Furthermore, the effective atomic number, as well as the effective monochromatic attenuation at a relatively wide range of monochromatic energy values, can be calculated at each point in the material being examined.

The DECT technique not only enables the removal of beam hardening effects but also provides considerable additional information about the material being examined than is possible when using a standard polychromatic beam. DECT allows the monochromatic attenuation at a range of values, the effective atomic number value, as well as the components in the basis decomposition (commonly a water and iodine pair) to be measured throughout an object.

The technique overcomes the historical problems of distinguishing materials of different

atomic number and density; it identifies the component of attenuation from the Compton effect (proportional to mass) and the photoelectric effect, which relates to atomic number (Alvarez and Macovski 1976). Material decomposition into components of significantly disparate atomic number has been shown to be a useful tool for this approach (Kalendar, Klotz, and Kostaridou 1988) and is the one used in this technique, with decomposition into water ($Z_{\text{eff}} = 7.42$) and iodine ($Z = 53$).

Water is chosen as it corresponds to the universally accepted zero value for polychromatic HU values on conventional CT. Iodine is a useful pair because it has a sufficiently high atomic number to give good material separation within the range of substances normally encountered in pottery, as well as being a commonly used CT contrast agent for biological scanning, and has been well characterized on modern CT units.

MicroCT versus conventional CT

Micro- or nanoCT has become more readily available for researchers recently and is characterized by the extremely high-resolution scans that it is possible to acquire, ranging from a few

hundred micrometers down to 50 nm. Its heritage is one of industrial scanning and thus it can often employ higher X-ray energies than available in clinical scanners, reducing the effects of beam hardening, and can even be successfully used for metallic objects.

However, the higher resolution imaging comes at considerable cost, since the field of view is proportionately reduced, sometimes down to $< 20 \mu\text{m}$, and scan times can run into many hours even before reconstruction of images is taken into account. In comparison, the scan field of view for conventional polychromatic CT and DECT is 500–650 mm in diameter and up to 2,000 mm in length, depending upon the scanner used. The scan times rarely exceed 20 seconds, with image reconstruction taking seconds to minutes, reflecting their clinical heritage.

DECT analysis of pottery

Using a GE HD750 (GE Medical Systems, Milwaukee, Wisconsin) 128 slice fast switching, DECT scanner, and pottery from known sources and of specific compositions (Figure 1), the authors compared the accuracy of DECT with the more traditional analytical techniques



Figure 1 Pottery sherds arranged on the bed of the DECT scanner.

of petrographic analysis (OM), ICP-MS, and ICP-AES (McKenzie-Clark 2012).

The total scan time was approximately four seconds, generating in the order of 650 MB of raw data, which were then analyzed using a GE Advantage Workstation and dual energy analysis toolset.

Each individual sample was assessed and a region of interest drawn with a total area of approximately 20 mm², to allow for the measurement of about 50 voxels (volume pixels—the smallest area that the scanner can measure on this reconstruction).

The region of interest was carefully positioned so as to avoid the edges of the pottery fragments, which would lead to inaccurate readings. Where possible, the surface of the sample was also avoided so as to isolate the sample voxels to the fabric, rather than any surface coating material or residue build-up which may have been present.

For each voxel the following values were obtained: polychromatic HU (120 kVp equivalent); monochromatic HU (40–120 keV at 10-keV intervals, nine data series); effective atomic number (Z); material decomposition—water (mg/cc); and material decomposition—iodine (mg/cc). Individual samples were tested in order to assess the sample consistency using a 120-keV HU dataset. In each case the means, interquartile ranges, and outliers were identified, as well as a group analysis. Similar consistency was seen with the other values obtained.

DECT scanning of the ceramic samples established the mean composition as well as confidence intervals and standard deviations for each group. Once again, the example chosen was the 120-keV HU dataset, and similar confidence intervals and standard deviations were returned for the other values obtained.

To test the validity of the analyses, an unpaired t-test was performed between each of the groups. All group comparisons yielded a P-value of <0.001, with actual P-values of down to 10⁻¹²² between the most disparate groups.

To fully utilize the statistical significance of the analysis performed, a minimum cross-sectional examination area was chosen at 20 mm². This provided approximately 50 data points per sample, equivalent to a 5-mm-diameter section of the fragment that is distinct from the surrounding air.

The sample region of interest (ROI) requires at least one nonincluded voxel both above and below the plane of analysis because of partial-volume artifact. Consequently, at a voxel thickness of about 0.5 mm, this requires the ROI to lie mid-way through a sample of at least 1.5 mm thickness. Within the pottery sampled this gave a total of 1,315 data points, with 13 values measured per point, or some 17,000 values for analysis. Within those many measured values, 120 kVp HU was chosen, as it is representative of the most commonly used conventional or polychromatic CT acquisition spectrum.

Results

Analysis of the monochromatic attenuation values generated by DECT allowed intra- and intergroup comparisons to be made, enabling the similarity of samples from each fabric group to be determined. The technique also permitted analysis of the compositional uniformity within each sherd. All vessels were made from one piece of clay, but in each example the composition of the base, or foot rim of the vessel, varied considerably from the rim and wall of the sherd (McKenzie-Clark and Magnussen, in preparation).

This result brings into question the accuracy of traditional compositional analysis where most samples are removed from the base or foot rim because of the need to maintain the integrity of the sherd in order to analyze the vessel form. The results of this investigation indicate that the classification of fabric groupings, established by sampling vessel bases, may not be indicative of the composition of the remainder of the vessel.

DECT scanning also revealed that the density of the clay fabric varied considerably, indicating that the preparation of raw clay by potters and workshops was not consistent (Figure 2). The results suggest that particular workshops maintained stringent standards of clay preparation, while other manufacturing centers took a less rigorous approach. Moreover, in some workshops, considerable differences could be distinguished between the clay prepared by individual potters, suggesting that each potter worked the clay to suit their own preferences and method of

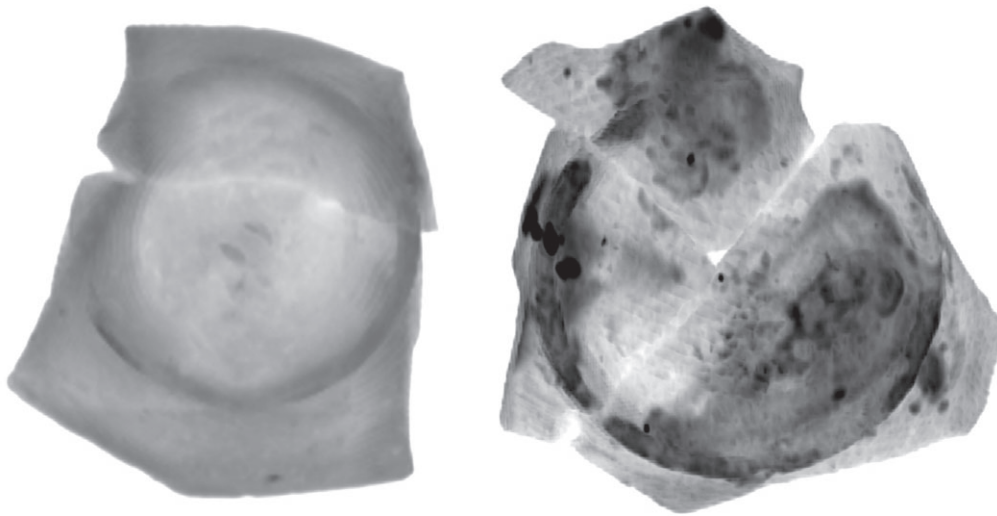


Figure 2 DECT scans reveal marked differences in the density and composition of the clay fabrics.

working (McKenzie-Clark and Magnussen, in preparation).

The compositional results achieved with DECT appear comparable to those generated by previous studies using OM, thin section analysis, ICP-MS, and ICP-AES (McKenzie-Clark 2012; McKenzie-Clark and Magnussen 2014). The results suggest that DECT has the potential to be a viable addition to traditional analytical methods and perhaps an alternative to destructive methods currently employed to analyze ancient ceramics.

Advantages of DECT

DECT scanning provides the composition of ceramic clays in terms of their effective atomic number, thus enabling samples to be compared to group analyses and other individual pieces. Compared with conventional analysis techniques, DECT has significant advantages, including:

- It allows multiple regions of interest to be sampled on each piece of pottery, thereby giving a comprehensive and thorough assessment of the vessel composition.
- Sample size can be controlled to provide reliable comparative evaluations across all objects of interest.
- Clay density throughout a given ceramic sample can be mapped and provides invaluable insight into the techniques of clay preparation used by the original manufacturer.
- During the entire DECT scanning process, the sample materials remain untouched and can be placed in plastic storage bags while being scanned, thereby securing the safety of the objects. This is particularly useful when scanning valuable, delicate, or fragile ceramics.
- Multiple sherds of pottery can be placed on the DECT scanning bed and data acquired in one pass of the machine.
- Scan times are quick (a matter of seconds), depending on the size of the object being analyzed.
- There is no need to retain the ceramics once the process is complete. Once scanned, the ceramic material is not required.
- The scan data can be stored for future study or reference and reinvestigated at any time, without the need to retain the ceramic object.
- Being a digital format, scan data can be readily exchanged globally, with ease.

Most importantly, unlike other analytical methods used to investigate archaeological ceramics, the technique is totally nondestructive. The raw data allow future analysis of the pottery, without the need to physically alter the original

ceramics, thus preserving heritage for future generations.

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SEE ALSO: ICP-MS and Material Analysis; Neutron Activation Analysis (NAA); Optical Microscopy; X-Ray Fluorescence Spectrometry (XRF)

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Ore and Smelting Slag

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Ores and smelting slag are, respectively, the main raw materials and by-products of metallurgy. As such, they are one of the major research foci of archaeometallurgical studies. The analysis of archaeological ores and slag can yield information about the metals being produced and underlying engineering parameters such as temperatures and redox conditions, the selection and manipulation of natural materials, and the efficiency of ancient technologies. Through large-sample comparative approaches it is possible to use slag analyses to reconstruct knowledge transmission, technological traditions, and their evolution in time and space in response to different environmental and cultural constraints. With comparatively limited curatorial concerns impeding scientific analyses, ores and slag can be among the most revealing material categories in the archaeological record. Their study has progressively become mainstream since the 1980s, after decades of neglect owing to their “industrial” nature and allegedly limited museological potential.

Ores are rocks that contain metals in such condition and quantity that they can be extracted in a cost-effective manner. Given the fluctuations in technology and in the value of metals in time and space, the attribution of a rock or geological deposit to the “ore” category is culturally contingent. Metal-bearing minerals are typically dense and colorful, and as such they have also been used as pigments and medicines or for lapidary work. In these nonmetallurgical contexts, the use of the term “ore” can be misleading and should be avoided.

There are as many ore types as there are rock types, each with their own constraints and potentials. For example, sedimentary ores (hydroxides and carbonates) tend to be near the surface and easier to exploit but smaller, whereas massive hydrothermal sulfide deposits are typically larger

but require higher investment and technological knowledge for mining and smelting.

The analysis of ores in archaeology often seeks to identify the nature of the rocks exploited, their grade (i.e., richness in metal content), and the types of metal-bearing (ore proper) and nonmetal-bearing (gangue) minerals that are geologically associated. These analyses can include a combination of mineralogical (e.g., X-ray diffraction (XRD)), chemical (e.g., X-ray fluorescence (XRF), inductively coupled plasma (ICP)), and microstructural analyses (i.e., by microscopy), together with a broader assessment of the geological context. In addition, ore analyses are useful to facilitate mass balance calculations (see below). Their chemical and isotopic composition can be used as a reference for provenance studies, providing a signature against which those of slag or metals may be compared.

A key challenge for ore analyses in archaeology is that of sample representativity. Often, the richest ore deposits will have been exhausted in the past, and hence those left behind at mines or geological formations are not representative of those that would have been used by the communities being studied. When broken ore fragments are found at archaeological sites, one can be more certain that these were extracted by past people, but the fact that they were discarded rather than smelted may be due to their not being of the desired standard; thus, they may not be representative as samples for grade assessment or mass balance calculations. This is in addition to problems such as the natural variability of geological deposits, meaning that often many samples are required to obtain a reliable characterization. Modern economic geology maps can be useful to identify potential ores used in the past, but archaeologists should be aware that these are likely incomplete: small and rich deposits exhausted in the past and/or lacking economic value in the present (and hence not included in modern maps) may be archaeologically relevant.

Mining was usually followed by beneficiation, which involved the mechanical preparation of the ore by crushing and sorting according to

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physical parameters such as color or density. This process seeks to achieve a material that is consistent and optimized for the subsequent smelting operation, in terms of particle size and composition/richness. Beneficiation sometimes involved a separate heating stage or “roasting” at moderate temperatures to remove water, sulfur, and other impurities as gas, and to increase the porosity and brittleness of the ore.

Smelting is a chemical reaction whereby metals are extracted from ore minerals, where they occur chemically bonded to other elements. In most cases this reaction takes place under temperatures higher than used for domestic or other craft purposes, and under a reducing atmosphere (i.e., one with relatively high carbon monoxide content). This environment is created by the burning of wood charcoal (or, more rarely, mineral coal) in a container such as a ceramic reaction vessel or crucible, or a larger heating structure or furnace (or, more rarely, a pit in the ground). During smelting, crushed ore minerals are made to react with gases so that they release the metal(s) of interest. This reaction can take from less than one hour to several days, depending on the reagents and scale of the operation. Most smelting reactions will lead to the formation of slag in addition to metal and gas. Slag forms as a liquid that contains the bulk of the ore minerals and oxides that were not reduced to the metallic state, in addition to fuel ashes, and molten ceramics from the crucible surface or the furnace inner lining. From an efficiency perspective, ideal slag is well reacted, fluid at relatively low temperatures, and devoid of the metal being smelted, thus ensuring a good separation between product and by-product. However, archaeological slag often deviates from this expectation, potentially reflecting a lack of technological skills, individual cost-benefit assessments that may require compromises on the above ideal in favor of other parameters such as fuel efficiency, or ritual constraints affecting practice.

Most preindustrial slag is dominated by iron oxide and silica, irrespective of the metal being smelted, as these are among the most abundant oxides on the Earth's crust. However, the proportions among these and other constituents will vary depending on their original nature, and parameters such as charge composition, temperature, atmosphere, and duration. As such, slag

constitutes a durable record of ancient technological practice, albeit a challenging one because of the potentially mixed material and behavioral signatures conflating in slag formation. It should be noted that very pure ores can be smelted without producing slag (“slagless smelting;” cf. Craddock 1995), and that some metallurgical processes other than smelting, such as metal refining or iron forging, can produce slag too. In addition, high-temperature industries such as lime burning, pottery firing, and glass making can produce amorphous fused debris that may be confused with metallurgical slag, although the latter tends to be denser because of its higher iron content.

Slag from individual smelts can occur as very small (<1 cm) nodules or vitrified layers lining crucibles from small-scale operations (Radivojević and Rehren 2016), or as large blocks exceeding 100 kg collected at the bottom of furnaces (Humphris et al. 2009)—or anything in between. Archaeologically, slag dumps can accumulate as relatively large scatters or even form so-called slag heaps amounting to tens of meters in diameter and weighing many thousands of tonnes. The morphology of slag lumps can be informative of the type of structure where it formed, and hence of cultural or temporal associations. For example, Late Neolithic copper smelting slag often occurs as very small nodules with sharp edges, resulting from the action of smelters who crushed it to retrieve metal globules trapped within after smelting in a crucible. In so-called slag-tapping furnaces, slag is drained while hot through a hole or arch at the base of the furnace: the resulting slag is typically more homogeneous and preserves tell-tale morphologies which can resemble a flat cake (if it solidified while floating on a pool of metal) or ropey textures such as those of flowing lava (if solidified during tapping). Bowl or pit furnaces will result in larger blocks of slag accumulating at the bottom of the furnace, in addition to amorphous, fist-sized chunks that solidify within the furnace, often in contact with charcoal and preserving impressions thereof. Furthermore, the original metal smelted can sometimes be identified by the corrosion of metal particles within the slag that appear as colored patches in the predominantly black slag; they can be green for copper, red or blue for iron, or white for lead and zinc.

Archaeometallurgists often carry out bulk chemical analyses of slag. These can be very useful not only in identifying the metal being smelted, but also in allowing mass balance calculations. These are particularly helpful when the composition of other system materials such as ores, technical ceramics, or fuel ash can be determined. Different models have been proposed to use these data to assess the efficiency of the operation (e.g., the proportion of metal from the ore left behind in the slag), to estimate the metal output per unit of slag, or to hypothesize the relative contributions of ore, fuel ash, and ceramics to slag formation (Thomas and Young 1999). Combining the slag bulk chemical composition with phase diagrams or other information from modern engineering literature it is also possible to estimate the melting point of the slag and furnace operating temperatures. In turn, these calculations aid in the assessment of how past smelters adjusted charge composition or operating conditions (Rehren et al. 2007). While all of these are estimates which can bear considerable margins of error, they provide quantitative proxies for cultural behavior that permit comparisons in space and time. As such, they can form the basis of studies addressing broader archaeological issues such as knowledge transmission, independent lines of metallurgical invention, or technological adaptations to changing environmental and cultural constraints.

It is essential, however, that chemical analyses of slag are supplemented by microstructural examination, typically by optical and/or electron microscopy (Georgakopoulou, Bassiakos, and Philaniotou 2011). This approach allows an evaluation of the extent to which the slag was fully molten, the presence of residual ore minerals or other particles that may help identification of the original charge, and the nature and composition of the metal left in the slag. For instance, inferences about technological parameters will vary depending on whether copper left in slag is bound in a silicate, as a copper oxide, trapped in a sulfide, or as ferruginous metal globules. When identified under a microscope, the nature and distribution of neoformed phases crystallizing in the slag is also informative of the conditions of slag formation: For example, wüstite (FeO) is indicative of highly reducing conditions suitable for bloomery iron smelting but excessive for copper smelting,

whereas higher valency magnetite (Fe₃O₄) is more compatible with copper smelting but can appear on the outer surface of any slag that was tapped out and solidified in contact with air. Some researchers undertake mineralogical or redox analyses of slag using techniques such as XRD or Mössbauer spectroscopy, but the texture or internal homogeneity of the slag cannot be evaluated without microscopic analyses.

Pioneer studies on archaeological ores and slag in the 1970s focused strongly on identifying early evidence of metal smelting and characterizing technical aspects that reveal past technological achievements. Especially since the 1990s, the scope of archaeometallurgical studies has expanded to cover virtually all metals and periods. Technical studies remain a necessary component, but information is used increasingly to address broader issues such as the social contexts of innovation, the evolution of sociotechnical systems, and metallurgical changes associated with variable constraints. There have also been successful attempts at direct dating of slag by radiocarbon, archaeomagnetic, or luminescence methods (Ben-Yosef et al. 2016).

SEE ALSO: Archaeomineralogy; Characterization of Metals and Alloys; Geoarchaeology; Metallography; Metallography and Crystallographic Texture Analysis

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Paper

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The term “paper” probably came from the Egyptian word “*papyrus*” used to describe writing material created from stems of *Cyperus papyrus*. A product similar to our modern paper was produced in the second century CE in China. It is commonly assumed that the first sheet of paper was made by a Chinese dignitary, Cai Lun, in the year more or less 105 CE. He watched the production of silk, which included washing the silk wool on special mats. Wetting and whipping silk wool with sticks resulted in leaving residual amounts of fibers on the mats. After removing the cotton wool from sieves, a thin layer of fibers formed specific structures, which after drying could be stored without losing their shape and served as a support for writing or drawing. It seems less clear now, after some Chinese archaeologists shed new light on this theory, pointing out that papermaking might have started even earlier and the importance of Cai Lun relied rather on him being the improver and popularizer of papermaking rather than an inventor (Jixing 2011).

There is common agreement that the use of cellulose fibers from the sap of mulberry, linen rags, or old fishing nets instead of expensive silk was proposed by the Chinese. The main method of paper production has been nearly the same for centuries. It is based on cooking vegetable raw materials in alkaline solutions to weaken bonds between fibers and facilitate slurry creation. Potash or lime solutions were used for this purpose. The fibers were suspended in water, then poured through sieves and delicately shaken to allow random distribution of the fibers, left to drain, pressed to form sheets of paper, removed from the sieves, and dried. The Chinese used milled gypsum as a mineral filler to increase the quality of paper and rice starch for sizing.

The use of different plants and sources of raw materials influenced the properties of created

structures that after drying could serve for writing. The know-how of paper production was kept secret for centuries, including such details as selection of fibers to obtain targeted features of the end product, including thickness (grammage) of the paper. Arabs started to produce paper around 751 CE. Bloom wrote that microscopic examination of medieval Arab papers occasionally reveals unprocessed threads and bits of cloth, indicating that the pulp was made mostly from rags (Bloom 2017). They were ground during time-consuming processes and boiled to form a slurry of fibers. While dried in a form of paper, starch paste was used to size paper sheets from both sides to obtain good writing properties and a fine appearance of the paper surface (Mahgoub et al. 2016).

Around 1100 CE, Italians began to produce paper and introduced water propulsion to drive machines shredding and fiberizing the plant material. Besides the use of hydro power, the first centuries of European papermaking did not bring changes in the production process until the invention of the printing press by Gutenberg in 1440. The search for a faster and cheaper way of paper production began in the first half of the fifteenth century with the rapid increase in the demand for this material. Replacement of the traditional raw materials was needed due to the lack of enough old rags for production. A French scientist, Rene de Reaumur, proposed the use of wood instead. Wood was used as a raw material already in 1769, but the first paper made entirely from wood pulp was not produced until 1840. Significant acceleration of production achieved by introducing paper machines with a continuous wire-mesh belt allowed formation of paper in ribbons instead of individual sheets. With modern machine-produced paper, fibers are not quite accidentally deposited. Most of them are arranged parallel to the direction of the ribbon length. This affects the properties of the end product, particularly with respect to the mechanical resistance of the paper, which is greater along the plant fibers. This is a fundamental difference between machine- and handmade papers, in which all the fibers are arranged quite

accidentally without affecting the mechanical parameters in any direction of the paper.

Although some changes in paper production have been introduced, the main steps are generally the same. They depend on chemical and mechanical processing of plant materials, draining and fiberting on the sieve, and drying and finishing the surface of the final product. Progress in the nineteenth century changed paper production dramatically. Very soon it became apparent that despite the progress in costs and speed of production, paper durability drastically decreased because it was made of wood and sized with a resin glue. Paper durability was limited to only a few decades, while paper produced according to the old technology could be stored for hundreds of years.

Regardless of the form, either sheets or a continuous ribbon, paper is a material made from mutually tangled plant fibers with walls that are made of cellulose (Andreasson, Forsström, and Wågberg 2003). Although paper can contain sizing substances, fillers, and dyes, cellulose determines the basic chemical and physical properties of paper. Thus, paper durability is directly related to cellulose durability, which can be heavily dependent on other substances influencing the rate of cellulose reactions and modifying paper preservation state. While rags were the source of long cellulose fibers, wood was soon recognized as a raw material of much worse quality. Additionally, resin glue used for sizing introduced into the paper structure significant quantities of acidic substances which lower the pH value of paper and were harmful to cellulose. pH is recognized as one of the basic parameters describing the state of paper, and the best value for prevention of deterioration should be neutral or slightly alkaline.

Taking the above information into account, it can be stated that when acidic compounds (resin glue and aluminum sulfate or wood pulp) were introduced in the modern production process of paper, they increased the initial acidity of the products and the syndrome of “acidic paper” became a common problem. The protection of all documents endangered by acidification required development of effective procedures applicable for routine mass deacidification of library collections. Nowadays, various inorganic and organic compounds can be used as active deacidification

agents. They can be applied by spraying, brushing, or immersing endangered objects in respective solutions (Potthast and Ahn 2017). Their effectiveness was tested many times and proved satisfactory for slowing down the chemical reaction responsible for increased paper brittleness.

Chemically, cellulose is a polysaccharide composed of glucose units whose number determines the degree of polymerization (DP). Vegetable fibers are made up of chains of different lengths, having variable DP: Native wood cellulose is characterized by a DP from 6,000 to 14,000, while the DP of cotton cellulose can be estimated as 20,000–30,000. The properties of paper depend on the DP of the cellulose. Breaking down cellulose chains leads to depolymerization of cellulose molecules. Intermolecular binding occurs when the distances between neighboring cellulose macromolecules do not exceed 0.25 nm, allowing formation of hydrogen bonds in so-called crystalline regions. The availability of crystalline areas to chemical reactions is limited. The variety of binding forces of cellulose molecules, as well as different degrees of crystallinity and polymorphism, are responsible for the fibers’ anisotropy. It is expressed in a tenfold higher breaking strength along fibers than in their lateral direction. Conversely, the ability to swell across cellulose fibers is about 200 times greater than in the longitudinal direction. Different fiber orientations in hand made traditional papers and modern machine papers enhance the differences between these two cellulose products.

Reactions between cellulose and reagents may occur simultaneously and depend on the speed of diffusion of chemical compounds into the molecule as well as the course of each reaction. Hydrolysis of cellulose may occur in both acidic and alkaline environments, leading to gradual shortening of cellulose chains (depolymerization). Alkaline hydrolysis requires both high temperatures and concentrated chemicals at the same time, so it is less problematic than acidic hydrolysis. The other problem mentioned quite often in the literature is oxidation leading to mixtures of cellulose molecules with variable degrees of oxidation. These molecules are typically characterized by a lower DP than cellulose, higher oxygen content, poorer strength properties, and higher solubility in alkaline solutions. The final products of degradation of oxidized cellulose

include sugar, and glucuronic and glucaric acids. In antique objects, hydrolysis and oxidation reactions most often occur simultaneously (Havermans and Dufour 1997). Depolymerization of cellulose and further decomposition (degradation) not only occurs due to hydrolysis and oxidation, but also very often these reactions are accompanied by the enzymatic action of microorganisms (fungi, bacteria) or a thermal and photochemical decay.

The quality of paper can be tested by learning about specific parameters including physical (e.g., fold number, folding endurance, tensile strength), optical (e.g., brightness, yellowness), and chemical (e.g., pH, DP) properties. These parameters can be measured by modern instrumental methods and the obtained results allow for paper quality assessment. Some tests of paper quality have been adapted to the needs of conservation research from the modern paper industry, but sampling of contemporary papers does not require a reduction of the size of the samples and can be even completely destructive, which is unacceptable for historical objects. For tests based on destructive measurements, model samples are used. Such model samples reflect basic features of real objects. A huge advantage of using model systems is that they can be subjected to artificial aging and even completely destroyed during investigations of the influence of variable parameters on paper durability (Becker et al. 2016).

SEE ALSO: Conservation; Conservation of Fibrous Materials; Conservation Science; Pollution and Heritage Conservation; Polymers in Conservation

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FURTHER READINGS

Paper Analysis

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Paper has played a key role in recording the development of culture all over the world. It is a multicomponent material that is mostly made from cellulose, with a small amount of organic and inorganic additives. The irreversible deterioration of historical paper is caused by several processes including acid hydrolysis, autooxidation, light, and the presence of microorganisms (María and Hervé 2011). In the conservation field, knowledge of the original morphology and paper surface texture is critical for the paper to be preserved as historical evidence. Because of the conservation value of historical paper, without any sampling or with a very small sampling, rapid and effective analysis methods are required.

To achieve this goal, many spectroscopic techniques have been developed for historical paper analysis such as Fourier transform infrared (FTIR) spectroscopy (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)), Raman spectroscopy (see RAMAN SPECTROSCOPY), nuclear magnetic resonance spectroscopy (see NUCLEAR MAGNETIC RESONANCE (NMR)), X-ray spectroscopy (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), laser-based spectroscopy (see LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS)), inductively coupled mass spectroscopy (see MASS SPECTROMETRY (MS)), atomic absorption spectroscopy, and X-ray photoelectron spectroscopy (see X-RAY PHOTOELECTRON SPECTROSCOPY (XPS)).

FTIR spectroscopy is an analytical technique used to identify molecular components and structures (the energy level of infrared (IR) light corresponds to the energy required to cause molecular vibrations). The IR spectra of a sample is collected by illuminating a beam of IR light on the sample, then using a spectrometer to record how much energy was absorbed (y-axis)

at each wavelength (x-axis). This technique was performed by Casoli et al. (2013) to understand the composition and inorganic filler types of one late-nineteenth-century newspaper. Cellulose pulp, wood pulp, and fillers (calcium sulfate dehydrate, calcium carbonate and silicates, kaolinite) were detected in their study. The results played an important role in the definition of micromorphological properties and roughness of the paper surface. In Zotti, Ferroni, and Calvini's (2008) study, the presence of fungi in biodeteriorated eighteenth-century etchings was verified, and the FTIR spectroscopy technique was used to check the composition of the paper surface. It worked well, particularly after the elaboration of the experimental data which enhances the significant differences in the spectra. This study also supplied further standards for deeper FTIR analysis.

Near-infrared (NIR) spectroscopy has shown its capability to analyze physical and chemical properties of wood-based materials while retaining their structure intact. In the range of 800–2500 nm, there are overtone or combination bands (fundamentals appear in the mid-IR region) due to functional groups such as C-H, O-H, and N-H. Because the molar absorptivity in the NIR range is typically quite small, nondestructive, fast quantitative and qualitative analysis can be achieved without special sample pretreatments. NIR spectroscopy could also be useful in investigating the chemical condition of washi artifacts (literally “Japanese paper,” which has played a vital role in Japanese culture since the introduction of paper from China in the early eighth century). Yonenobu, Tsuchikawa, and Oda (2003) compared the NIR spectra of two samples of antique washi paper with modern materials. They showed that NIR spectroscopy can detect change in the main chemical components of washi paper, since the obtained results were consistent with conventional sugar analysis; that is, the degradation occurs especially in the amorphous region of cellulose where depolymerization is induced dominantly by the peeling of end-groups in polysaccharide and hydrolytic reaction in alkaline conditions, which was also observed by the NIR second derivative change.

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Nuclear magnetic resonance (NMR) shows great promise for future use in damage assessment of historical documents. For instance, Blümich et al. (2003) nondestructively analyzed the degradation of historical books dating from the seventeenth century by (NMR) relaxation. A mobile NMR sensor (NMR-MOUSE) was employed, and experimental results indicated that although the sensor works strongly in inhomogeneous polarization, different degrees of paper degradation could be discriminated from the regularized inverse Laplace transform of the envelope of the acquired echo signals. Also, in Viola et al.'s (2004) study, a new portable NMR device was developed to test some aspects of the microscopic healthy state of the historical documents. It used nonionizing radio frequency electromagnetic waves and was easily transportable without hazard to people or the environment. Some pages of the *Codex Major* belonging to the *Collectio Altaempsiana* (1600–10) were examined; the NMR results provided indications of the spread of the deterioration process of the paper and the corrosion effect caused by the iron-gall ink.

X-ray fluorescence (XRF) is an analytical technique that uses the interaction between X-rays and a material to determine its elemental composition; this technique also demonstrates possibilities for detection of nondestructive elements of historical documents. In Manso, Costa, and Carvalho's (2008) study, paper documents from the eighteenth and nineteenth centuries were analyzed by energy dispersive X-ray fluorescence (EDXRF). Strong positive Spearman correlations between Co, Ni, As, and Bi were found in Dutch and Hespe watermarked papers. The concentration levels of these allowed distinguishing between Dutch and Hespe papers.

Several combinations of spectroscopy have been applied to paper analysis. Castro et al. (2008) investigated a Dutch map from the eighteenth century by using EDXRF, FTIR, NMR, Raman, and scanning electron microscopy coupled with energy dispersive spectrometry (SEM-EDS). All aspects of the sample were determined in an elemental and molecular way. The cellulosic support was characterized and its state of conservation was evaluated. Moreover, paramagnetic impurities were detected together with copper metallic chips. The colors present in some areas of the map were analyzed, and vermilion, carbon black, and

organic colorants were found. Barrett, Ormsby, and Lang (2016) undertook nondestructive analysis of 1,578 paper specimens made between the fourteenth and nineteenth centuries to better understand changes in paper composition over time and how these variations might affect paper stability during long-term natural aging. Here, gelatin content and color were determined using ultraviolet/visible/near-infrared (UV/Vis/NIR) spectrometry; residual metals were measured using XRF.

Other advanced methodologies are reported for the study of ancient paper. Gibbs et al. (1997) developed a simple, rapid, high-performance liquid chromatography (HPLC) method. It gave excellent separation of the protoberberine alkaloids and allowed the unambiguous detection of berberine in dyes extracted from tiny fragments with dimensions of 3×1 mm removed from the edge of ancient paper samples. Examination of 25 ancient papers contemporary with the Dunhuang *Diamond Sutra* (the world's oldest dated printed book) indicated the chemical components, including not only berberine but also previously unsuspected yellow compounds of palmatine and jatrorrhizine.

Deterioration of historical papers is caused by several processes, including acid hydrolysis and autoxidation due to the presence of metal ions contained in inks or pigments. Migration of the metal ions into surrounding paper material can cause huge damage to ancient documents. Fluorescence labeling of carbonyl and carboxyl groups in combination with gel permeation chromatography multiple angle laser light scattering (GPC-MALLS) was used to determine not only the extent of hydrolysis but also the concentration of oxidized functionalities within very low sample amounts (Henniges et al. 2016). An in-depth chemical and mathematical analysis of the aging processes for Hanji (traditionally used in Korea) is presented by Jeong et al. (2014). The aging of Hanji paper, resulting in hydrolysis and oxidation processes, was addressed using selective fluorescence labeling of oxidized groups in combination with GPC, providing profiles of carbonyl and carboxyl groups about the molar mass distribution.

Recent technical and scientific reports have shown that the main chemical reactions occurring in paper during aging were well identified using

noninvasive analytical spectroscopic techniques. The combination of several techniques could enhance historical paper analysis. On the other hand, since the multicomponent structure of paper complicates the analysis of ancient paper, a statistically relevant database of reference is required for data validation and practical use in further research. Moreover, conventional noninvasive analytical techniques require the data from a single point or a small portion of measured papers. Depending on the uniformity of the quality attribute within each historical paper, it might be necessary to repeat the data acquisition at several positions. This process takes a long time, even for low spatial resolution. A high-resolution and fast-speed method is expected to be useful for the evaluation of historical paper. Furthermore, sometimes artificially degraded papers were used for sampling instead of natural ancient ones; this has the advantage of sampling without using precious historical documents, and of improving the variance of experimental samples. However, the correspondence between artificially degraded papers through hydrolysis and oxidation processes and the natural aging process is still not clear, and needs to be proved in future studies.

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Perfumes and Cosmetics

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Introduction

The first material support on which color was applied was skin, alive and dead. Traces of red ocher found on the bones of the Lady of Paviland (ca. 33,000 BCE), in southern England, signal the antiquity of the association between color, skin, and funerary rites. Similarly, in ancient Mesoamerican societies, skin, red color, and funerary rites have been associated since at least the Middle Pre-Classical period (ca. 1200–300 BCE). Through this practice, reddish body coloring materials, as a metaphor of the blood, were thought to confer life on the dead corpses following the symbolic logic of sympathetic magic, according to which “same begets same.”

Physical–chemical analyses and historical–cultural studies of these first body colors, and their successors in the Ancient World, have revealed connections between cosmetics, culture, and society, allowing those associations to be traced through antiquity. For this reason, the study of the preparation and use of cosmetics and perfumes in ancient societies has been the center of attention of various research groups at universities, research centers, and museums throughout the world. Since the 1990s, pioneering results have been obtained by research teams in France, Italy, and the United Kingdom principally. Success has largely resulted from the fact that these teams have optimized very precise physicochemical protocols based on the

combination of several analytical techniques (e.g., Walter et al. 1999; Gamberini et al. 2008; Van Elslande et al. 2008). These techniques include in actuality the use of light microscopy (LM), ultraviolet visible spectrophotometry (UV-vis), scanning electron microscopy electron dispersive spectroscopy X-ray (SEM-EDX), X-ray diffraction (XRD), X-ray fluorescence (XRF), Fourier transform infrared spectrometry (FTIR), voltammetry of microparticles (VMP), Raman spectroscopy (RMS), gas chromatography–mass spectrometry (GC-MS), and high-power liquid chromatography (HPLC). The combination of these techniques, capable of diagnosing mineral (SEM-EDX, XRD, or XRF), organic (GC-MS, HPLC), and hybrid organic–inorganic substances (VMP, RMS, FTIR), offers us the possibility to understand the technology of cosmetic and aromatic science in antiquity, and in consequence the link between materiality and cultural significances in ancient body colors and fragrances.

The methodology for the study of cosmetics and perfumes in antiquity required, as a consequence, interdisciplinary research teams composed of physicists, chemists, geologists, botanists, pharmacists, archaeologists, historians, historians of art, and anthropologists, in order to identify the preparation and use of these ancient cosmetics and perfumes in present communities.

For its part, written sources from ancient societies contain valuable information concerning additional ingredients that were probably incorporated into the cosmetic and perfume recipes used in antiquity, such as fragrances. These texts cite a number of such scented essences, which can help us to complete the formulation of archaeological scented cosmetics—very common in antiquity—and aromatic substances. These same written sources tell us that each one of these scents had specific uses, linked to specific ceremonies. Rose fragrances, for example, were recommended for banquets or *symposia* (Bourliascos 2004, 22), while the fragrance obtained from the saffron flower was required in ancient Aegean rites of passage, such as in the festival of the *Brauronias*, the ceremony of passage during which 12-year-old Greek girls ceased

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to be *arkatoi* (girls) and became *osas* (women), according to historical writings such as *Lisistrata* by Aristofanes. The association between saffron, blood, the goddess Artemis, and the initiation of female fertility during this ceremony explains the symbolic and ritual meanings of saffron color and fragrance during the occasion (Vázquez de Ágredos 2011). In the New World, some chroniclers and dictionaries dating from the Colonial period describe fragrant flowers used by ancient Mesoamerican societies for different ceremonial purposes. Aromatic flowers used to prepare perfumes in antiquity were depicted in ancient art. Thus, the study of iconographic sources provides an important testimony with regard to this topic.

Cosmetics and perfumes in the Old World

In Ancient Egypt, many documents and objects, written texts, paintings, statues, artifacts, and toilet accessories support the fact that green and black make-ups were extensively used for their aesthetic, religious, and therapeutic properties. Cosmetics used to play an important role in everyday practices and during ritual and burial ceremonies. Make-up, named *ouadjou* when green and *mesdemet* when black, was part of a list of funeral offerings, including food, unguents, and oils, necessary to ensure the comfort of the dead person in the afterlife. Make-up containers were put inside the tomb to help the dead in the ceremonies involving purification in the afterlife.

The chemical study of 3,000- to 5,000-year-old cosmetics sampled from such containers made of stone, wood, or reed has shown that a restricted range of lead-based substances were used in developing a complex art of formulation (e.g., Walter et al. 1999). Three-quarters of the substances are lead-based compounds and are white, gray, or black. SEM and quantitative XRD have allowed us to identify four main phases: galena (PbS) for dark tones, and three white materials—cerussite (PbCO_3), phosgenite ($\text{Pb}_2\text{Cl}_2\text{CO}_3$), and laurionite (PbOHCl). It has been demonstrated that the last two minerals were synthesized, in particular from the lack of such compounds in and around Egypt, and this is

corroborated by a number of ancient texts from the Greco-Roman period. As these documents mention that these chemicals are good for eye and skin care, they were likely added to Egyptian make-up to confer therapeutic properties to the cosmetics. Today, the well-established toxicity of lead compounds has completely overshadowed their potential health benefits. New insights into the biochemical interactions between lead(II) ions and cells were obtained by electrochemical analysis of the biological interaction between cells from skin (keratinocytes) and submicromolar concentrations of Pb^{2+} ions in water (Tapsoda et al. 2010). Specific oxidative stress responses by the cells were observed, consisting essentially of the production of nitrogen monoxide (NO), which is known to play a role in stimulating nonspecific immunological defenses in tissues. One may then surmise that lead compounds with very low solubility (such as laurionite and phosgenite) were deliberately manufactured and used in ancient Egyptian formulations to prevent and treat eye illnesses by promoting the action of macrophages.

Concerning cosmetic typologies in use among the Phoenicians, little is known and generally references are from bibliographic Latin sources. In the Sicily museums (Palermo, Trapani, Marsala, Mozia) an important collection of Phoenician and Greek unguents showed white, black, blue, and red powders. XRD, FTIR, and RMS revealed two types of white samples: some mainly composed of gypsum and anhydrite and others of lead white (cerussite and/or hydrocerussite) and litharge. The second type of cosmetic corresponded to the most famous Greek make-up, called *psymition* in Greek and *cerussa* in Latin, used by women to whiten their faces. Lead white is a bright-white pigment with excellent coverage capabilities, because of both its high refractive index of light and its chemical synthesis technique that can, under certain conditions, produce the forming of very small grains with a platelet shape originating from the layered crystalline structure of hydrocerussite. The other materials suggested that, for the same use, alternative materials, cheaper and more readily available, could be employed.

The love of Phoenicians for the color red is evident from the great number of red powders, used on cheeks and lips: hematite, cinnabar, red lead, and the very rare lead chromate. The

materials' heterogeneity used for make-up, even, for example, in comparison to the Roman culture, revealed a palette less extensive and less refined. Classical sources such as Pliny and Ovid report exotic and sophisticated ingredients for Roman cosmetics. Instead, analysis of Pompeian cosmetic powders suggest a more economic and simple daily *cosmesis*. The numerous black powders were mostly made of carbon (soot) and used for eye and eyebrow outlining. Certainly, soot was an economic and available alternative to more expensive Egyptian *kohl* or less common *stimmi*, synthesized by heating lead and sulfur, not found in Pompeian powders. The white powder contained principally calcite and gypsum, and sometimes cerussite and aragonite (white shell). Calcite was described as a foundation, and it is more common than lead carbonate (*cerussa*), rare in analyzed samples from the Roman period, but often mentioned in the literature. The pink make-up was a mixture of several products, often hematite (ocher) lightened with a white pigment (often calcite). Only in one case, surface-enhanced Raman spectroscopy (SERS) use permitted identification of a plant from the Rubiaceae family used to color the clay instead of the expensive *purpurissum*: Pliny speaks of "purple of Pozzuoli" gotten with *Rubia tinctorum*. Finally, analysis of these Roman cosmetics from Pompeii and results obtained in Gaul and Germany have shown the use of materials more commonly found in nature (Welcomme et al. 2006). Black powders, usually used to outline the eyes, were mostly prepared with simple carbon (vegetable or animal). A blue powder consisted of the famous Egyptian blue.

Body colors and fragrances in the New World: Mesoamerica

In accordance with the first physicochemical results obtained in recent years, in ancient Mesoamerica the coloring materials used to prepare body colors were calcite (CaCO_3), clays, gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$), and diatoms (*Bacillariophyta*) (white); charcoal, galena (PbS), and manganese oxide (MnO) (black); jarosite ($\text{KFe}_2(\text{SO}_4)_2(\text{OH})_6$), limonite ($\text{Fe}_2\text{O}_3 \cdot n\text{H}_2\text{O}$), goethite (FeOOH), and hematite (Fe_2O_3)

(yellow); and red earths (varieties of hydrated iron oxide), hematite, specular hematite (Fe_2O_3), ilmenite (FeTiO_3), and cinnabar (HgS) (red and orange). Written and iconographic sources also describe the use of blue body colors by ancient Mesoamerican societies, probably prepared with indigo (different species of *Indigofera*, such as *Indigofera suffruticosa*, *Indigofera mucrolata*, and *Indigofera jamaicensis*), which still have not been identified by physicochemical analyses.

On some occasions, these body colors presented a simple formulation, composed of only one element: the chromatic pigment-matter itself. However, it is more common to identify mixtures composed of two to five components. It is in these composite cases that we can properly determine their intended formulations and technical recipes. In body colors discovered in the neighborhood center of Teopancazco (Teotihuacan), for example, the three most recurrent components in those formulations were the pigment itself, an organic additive, and mica. These constituent components were found in combinations of two constituents (pigment₁-pigment₂; pigment-mica; pigment-organic additive) or combinations of all three constituents (pigment-organic additive-mica; pigment₁-pigment₂-mica; pigment₁-pigment₂-organic additive; pigment-organic additive₁-organic additive₂) (Vázquez de Agredos, Pascual, and Manzanilla 2016). A fourth component, clay, was regularly encountered, albeit less often. We believe that at Teotihuacan the purpose of many of these formulations was to create body pigments which not only served to paint the body but also conferred hygienic/medicinal properties on the skin. In fact, those combinations contributed to these cosmetics three qualities: brightness, aroma, and medicinal properties. Some body colors, such as cinnabar and galena, and mica (biotite-type mica) contributed the brightness. Choosing biotite-type mica enabled producers to recreate yellow and red cosmetics that were "dotted" with a translucent orangey-amber or reddish glitter, which is the chromatic effect given off by biotite. On the other hand, a lot of body colors from Teotihuacan contain an aromatic organic additive, normally pine resin (*Pinus montezumae*), chia oil (*Salvia hispanica* L.), or a mixture of both. Technically, a resin is insoluble in water; this means that in order

to agglutinate color that can spread on the skin, an alkaline solution or oil is required. Oil applied to the body colors a medium texture that was different from the plaster obtained by mixing only pine resin with the cosmetic; it was also different from the oily fluidity of some body colors in which only chia oil was identified. This combination likely produced three different textures with different viscosities. Each formulation also provided its own scent to the body pigment. Lastly, we should not forget the strong rituality that impregnated each of these aromas; pine resin, for example, plays an important role in the religious beliefs and daily lives of ancient Mesoamerican societies, which also documented the presence of body colors mixed with this type of fragrance substance. In the case of ancient Mayas, such products were found as traces of pigments introduced in royal tombs in Mesoamerica as funerary offerings, or otherwise used to embalm the interred dynastic corpses. Preliminary results collected in recent years—which, incidentally, are the first results to be obtained after more than a century of archaeological activity in Mesoamerica—suggest that they are perfumed ointments with cosmetic properties. In other words, they are body unguents or lotions comprising color and aroma. In this sense, we have identified triterphenic compounds typical of bursera-type resins, such as copal (*Bursera copalifera* L.), used to agglutinate and aromatize cinnabar-based (HgS) body pigment, which was used to embalm the Red Queen of Palenque, a high Maya dignitary and possible consort of King K'inich J'anaab Pakal (603–683 CE; Late Classic) (Vázquez de Ágredos et al. 2015). Cinnabar thus treated was likely destined to slow down postmortem degradation and putrefaction of royal corpses, given that the mercury contained in its composition confers this retarding effect. This interpretation seems even more reasonable because, in accordance with inscriptions found in royal tombs, the ritual preparation of the deceased bodies could last for up to ten days, long enough to risk unpleasant odors and decomposition stench during the public funerary pomp, especially in the jungle of the Maya Lowlands. Likewise, we have recently identified diterphenic compounds used with red body pigment produced by iron oxide (Fe_2O_3) and mercury sulfur (HgS), which were found

in a funerary chamber inside Lundell Palace in Calakmul (Early Classic).

Thus, the first physicochemical results obtained on ancient cosmetics used in Mesoamerican societies described body colors prepared with the same coloring materials employed in other societies from the Old World (calcite, galena, jarosita, and hematite, among others), with the exception of blue and green cosmetics. These body colors were used in daily life, in accordance with writing and iconographic sources, but also in funerary contexts as offerings or on shrouds. Frequently these body colors or cosmetics were mixed with organic substances with aromatic properties, and/or in some formulations with luminous materials, such as mica.

Epilogue: the versatility of uses of ancient cosmetics and perfumes

The magical/ritual and medicinal properties of most pigments and aromas used to prepare cosmetics and perfumes in ancient societies from the Old World (Sumer, Egypt, Greece, Etruria, and Rome) and New World (Mayas, Teotihuacans, Zapotecs, Tarascos, Mixtecs, and Aztecs) explain how their physicochemical identification has allowed a better understanding of the cultural and functional aspects of these corporal pigments of malleable texture and pleasant fragrance. In other words, the study of cosmetics and perfumes opens the door to study color, aroma, drugs, and magic in antiquity and their connection with religious practices that cohered human groups and gave them a sociocultural identity.

This is the case, for instance, in medicine, where a raw material such as hematite (Fe_2O_3) and galena (PbS) was used in ancient Egypt since pre-dynastic times, not only as a pigment and/or cosmetic but also to treat illnesses and manufacture amulets. This coloring material was used as a cosmetic and medicinal substance by the Aztecs in Post-Classic times, as described by Martin de la Cruz in *Libellus de Medicinalibus Indorum Herbis*. In the same way, in ancient China, cinnabar (HgS) was used as a pigment, drug, and important alchemical ingredient. Finally, the use of diatomaceous earth in medicine and cosmetics dates back to ancient Mesopotamia. It

was used because of its antiseptic, antibacterial, and fungicidal properties, which act upon the skin as a barrier against germs, bacteria, and fungi, just as do algae (Kumar et al. 2013). These and other properties, like the antioxidants and anticoagulants that some species contain, were known and applied for medicinal use in ancient Near-Eastern and North African societies. The medicinal properties of diatomaceous earth are further attested in ancient populations of Central Mexico, in accordance with prescriptions from *Libellus de Medicinalibus Indorum Herbis*.

SEE ALSO: Archaeological Sciences; Archaeometry; Bodies and Embodiment; Characterization of Pigments; Chemistry in Archaeology; Dyes; Material Culture; Pigments and Binders

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Petrography and Ceramics

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History of petrography and ceramics

Petrography has a long history as a method for studying ceramic materials, and was developed in geology even earlier. It is used to investigate raw material sources, fabrication methods, functions, exchange networks, technological styles, use histories, and deterioration products. A small sample is cut from a ceramic shard, attached to a microscope slide with an epoxy resin, and ground to 30 μm thickness. At this standard thickness, minerals show a variety of optical properties that can be used to identify them under a polarizing transmitted light microscope. Both plane polarized light and crossed polarized light are used, as each provides information on different mineral properties. While clay minerals themselves, because of their very small size, cannot be discerned in thin sections, larger additives and minerals co-occurring with the clay can be identified. In addition to mineral identification, thin sections reveal information about porosity characteristics, decorative layers, and textures such as the amount, size, shape, and distribution within the matrix of larger particles that occur naturally in clay deposits or that were added by the potter to improve working, drying, firing, or the use properties of the clay.

This technique was used for answering archaeological questions regarding ceramics as far back as the early 1940s. For example, at early excavations of ancient Troy, petrography was successful at distinguishing local from imported wares, examining chronological differences among ceramics, identifying fabrication methods, and deducing the degree of control over firing. Over the following 75 years, major advances have been made by ceramic petrographers working all over the world, on many types of ceramic materials

and in the service of a wide range of research questions (Reedy 2008; Quinn 2013; Ownby, Druc, and Masucci 2017).

Characterization of inclusions for grouping, provenance, and exchange network studies

Many successful characterization studies addressing archaeological questions about workshop groups, provenance, and the extent of trade and exchange networks have focused on thin-section analysis of the nonplastic inclusions found in ceramics (Figure 1a). These inclusions can occur naturally in clay deposits or can be deliberate additions (often called “temper”) of the potter. Such inclusions improve the working, drying, and firing properties of clay and can impact the use properties of ceramic materials. Typical inclusions are rock fragments, grog (ground ceramic fragments), organic matter, sand, and other materials. Identifying the type of inclusions present and the size, shape, distribution, and abundance of each type of inclusion can be helpful in characterizing, grouping, or comparing ceramics and determining possible sources of raw materials.

In addition to identifying what inclusions are present, it is also often useful to calculate the area percentage of a shard occupied by inclusions (as a measure of the volume percentage chosen by the potter); the relative amount of each grain type; and minimum, maximum, and average grain size or shape. Methods to obtain these data can include visual estimation aided by published visual estimation charts, taking measurements with a microscope eyepiece graticule, point counting, and digital image analysis. Beyond focusing on the inclusions in isolation, Ian Whitbread (1995) pioneered the application of descriptive and statistical techniques from sedimentary petrography and soil micromorphology to characterize and group ceramic fabrics, and has successfully used that approach to answer a number of archaeological research questions in the Aegean.

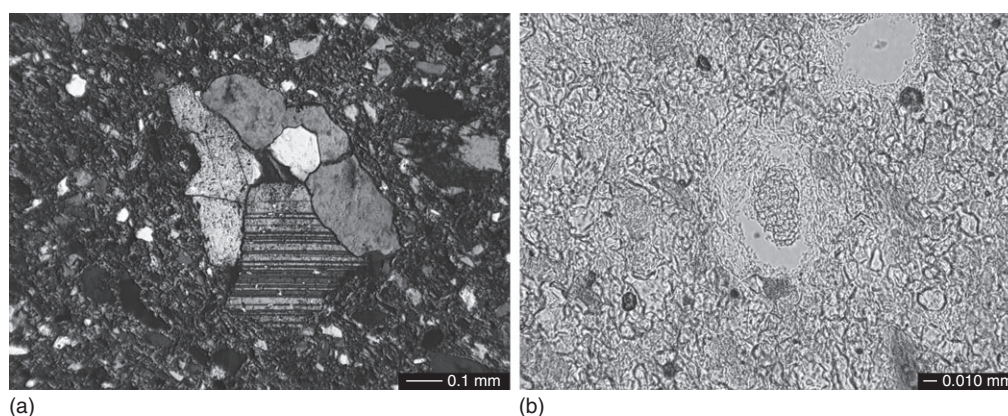


Figure 1 (a) A thin section (crossed polarized light) of a low-fired ceramic shows large, angular granitic inclusions, most likely from a crushed rock additive (temper). Many smaller quartz and feldspar grains appear within the clay matrix. Some may be natural inclusions in the clay, others may have flaked off of the granitic temper. (b) In a high-fired ceramic (plane polarized light) the original minerals that were present have been transformed into new high-temperature phases. Two large, clear, rounded pools of silica glass formed where quartz melted; the one in the center is partially covered by minute tile-shaped grains of cristobalite. Tiny mullite needles fill the glassy matrix where all feldspars have melted.

Source: Figures published with permission of the author. Previously published in Reedy, Chandra L. 2008. *Thin-section Petrography of Stone and Ceramic Cultural Materials*. London: Archetype Publications.

Petrographic studies involving the identification of rock fragments in ceramics have revealed a wide range of rock types such as obsidian, tuff, pumice, basalt, andesite, sandstone, limestone, dolomite, chert, mudstone, granite, phyllite, schist, marble, quartzite, and many others (Reedy 2008; Quinn 2013). One example of the many successful ceramic petrography studies that have focused on the analysis of rock fragments is Maggetti (2005). In that case, the question of interest was the extent to which the Alps served either as a barrier to or as a passage for ceramic trade in prehistory. A total of 454 shards from ceramics from the Laugen–Melaun (Luco–Meluno) culture in northern Italy, eastern Switzerland and Liechtenstein, and western Austria were examined in thin section. Many of the ceramics from northern Italy contained volcanic rock inclusions (rhyolite) that could be traced to rocks from that region, so they clearly represent local or regional ceramic production. Many ceramics containing the same rhyolite inclusions were also found in southeastern Switzerland, which lacks local sources of rhyolite; the find indicates that trade in ceramics occurred along

that route. However, the percentage of imported versus local wares decreased significantly over time (from 70% in the eleventh century BC to 10% by the sixth century BC); and no imported rhyolite pottery was found north of the Alpine crest in Switzerland, in Liechtenstein, or in Austria (serpentine rock fragments were found in those ceramics instead). This study illustrates the fact that rock fragments found in ceramic materials can often be traced to specific geological sources, so they are often useful in provenance studies that can illuminate archaeological questions about local production versus long-distance trade and exchange.

A “grog” temper refers to the addition of crushed fragments of previously fired ceramic pieces. These often come from shards of broken pottery. If the shards used as a source of grog derive from the same clay as the ceramic objects they are tempering, this is an advantageous additive, because there will be a close match in physical properties. Grog can be a good additive for clay with few natural mineral inclusions and needing some temper to improve drying and firing performance. However, grog is often just

one of a mix of tempering additives used. Grog can be difficult to identify with certainty in thin section, because it may look quite similar to argillaceous rock fragments derived from sedimentary material such as lithified clay, mud, or silt. The presence of a slip or glaze retained from the original shard can, however, securely identify the presence of grog.

As a variation on grog, sometimes small balls of clay were dried, fired, and then used as a deliberately manufactured temper material. Potters may choose this approach if there are no natural sources of potential additives (such as sand or rock deposits) close at hand. Sometimes the preference for manufactured temper is found even where other, natural additives are available. For example, Vincent (1988) found that manufactured grog was used in northeastern Thailand on the Korat plateau to control the shrinkage qualities of the local clays. The sedimentary rocks available on the plateau have a wide range of expansion rates; so, where clay quality is marginal, adding a lithic temper could be problematic. Control over the physical properties made the additional investment in time and fuel required to prepare the artificial temper worthwhile.

Sand, a common natural component of clay deposits and a frequent potter's additive, is comprised mainly of quartz. Frequently, quartz-rich sands from different locations appear at first glance to be so similar that they may be considered undiagnosable. However, by combining geological maps, field collection of sands, and appropriate statistical techniques, the petrographic analysis of sand in ceramics becomes more useful for archaeological studies. In a groundbreaking study of sand additives in ancient ceramics from central and southern Arizona, geological maps were used to construct preliminary diagrams of distinct sand composition zones along a river system, and then sand samples were collected from streams in that system (Heidke and Miksa 2000). Quantitative data on quartz amount, size, and shape from the sampled sands were used for statistical analyses to refine the original diagrams and to derive a mathematical function to best discriminate between sand locations. This discriminant function was then used with ceramic thin sections, to identify the most likely location where potters collected their sand. Ceramic production and

distribution patterns could be identified. In addition to the analysis of the quartz content of sand, sand tempers can often be characterized using other common constituents of sands such as feldspars, iron oxides, calcium carbonates, micas, and organic material. Sand-tempered ceramics can vary greatly in the presence, size, amount, or relative proportion of these different components.

Organic materials often serve the function of a temper additive in ceramics. If pottery is fired under reducing conditions, this material often remains charred in places and may be identifiable. Agricultural waste, such as the straw or stems from crop plants, may be seen. Other organic materials that have been identified in thin sections of ceramics include seeds or husks, animal dung, phytoliths, animal hair, feathers, textile fragments, and moss fibers. If the pottery was fired in oxidizing conditions, most or all of the organic matter may burn out during firing. Large pores may remain; these can be advantageous for various uses, such as in cooking pots or water storage vessels. Often some carbon residues may be seen along the edges of these pores, offering evidence that organic material was originally present. Quantitative pore analysis may help identify the amount of temper used, and the pore shapes can give clues as to what type of organic matter may have been used.

In low-fired ceramics, the nonclay minerals originally present as natural or added components remain unchanged or only slightly altered after firing. In this case, combining the use of geological maps with field surveys and the collection of comparative raw materials has emerged as an extremely useful approach to thin-section petrography that aims to identify specific sources of raw materials (Ownby, Druc, and Masucci 2017). This procedure takes full advantage of the geological roots of thin-section petrography and of the range and type of information viewable in thin sections. While early studies mainly focused on identifying the geological sources of rock-fragment additives, there are now many studies involving the characterization of clay deposits, with their natural impurities of larger nonclay particles.

Petrography and characterization of ceramic production methods for technological studies

While many petrographic studies of ceramics focus on the characterization of nonplastic particles (whether natural inclusions or deliberate additions) and on identifying geological sources of raw materials in order to answer questions related to workshop locations and trade and exchange connections, there are many other research questions that can be investigated through thin-section petrography. Foremost among these are questions related to the *chaîne opératoire*. Thin-section petrography can reveal information about clay selection and processing choices, object fabrication methods, firing conditions, and decorative techniques.

Clues as to clay preparation methods may be found in thin-section studies of the appearance of the clay matrix and of the distribution of coarser nonplastic components that are often present in clay deposits. For example, a clay paste with a very homogeneous appearance in grain size, content, and distribution may indicate that considerable effort was expended in clay-processing steps. By contrast, if little effort was spent on grinding, sieving, and mixing the clay, thin sections may show lumps of unevenly colored clay distributed here and there within a matrix of uneven distribution of the nonplastic particles. Wedging and kneading steps can eliminate many of the larger air bubbles within the clay matrix and produce a relatively uniform distribution of fine air bubbles. Thin sections that show many voids of varying sizes may be an indication that little wedging and kneading were done; whereas voids of relatively small and uniform size and distribution may indicate more thorough processing and preparation of the clay (Reedy 2008; Quinn 2013).

In one example, Velde and Druc (1999) used thin-section petrography to contrast the paste preparation methods of fine-grained *sigillata* ware and coarse-grained Neolithic wares in central France. The homogeneous mix of clays and small temper grains in the *sigillata* ware, with even distribution of fine grains and an even texture, indicated that careful steps in the preparation of

the paste included crushing, sieving, and impurity extraction. Thin sections of the Neolithic wares, by contrast, showed a very irregular distribution of grain sizes; there was also a “zoning” effect created by patches of fine grains interspersed with areas of larger grains. In this case, the paste was made from an inhomogeneous clay, which was not homogenized after extraction; it did not appear to have been ground, sieved, or mixed.

Ceramic-forming and fabrication methods can also be investigated through thin-section petrography in conjunction with a study of shards and whole vessels, and often with input from ethnographic work and replication studies. Thin-section analysis may reveal clues not visible through surface examination alone. For example, the orientation and alignment of platy particles such as micas or other elongated inclusions, and of voids or pores, can help differentiate forming methods such as use of a wheel, coiling, paddle and anvil, or building in segments (Middleton and Freestone 1991; Gibson and Woods 1997; Velde and Druc 1999; Reedy 2008; Quinn 2013).

While thin-section analysis of low-fired ceramics can help identify the geological source of the mineral and rock inclusions, with high-fired ceramics the original minerals are transformed into new, high-temperature minerals (Figure 1b). This is the case with many Asian ceramics, for example, which are often stonewares or porcelains. In this case, thin-section examination of minerals in ceramic bodies and glazes can provide information about firing and cooling regimes. For example, quartz grains that undergo significant thermal shock from rapid heat rise can crack. If held in the kiln for long enough at high temperatures ($\geq 1250^{\circ}\text{C}$), quartz can convert to cristobalite, which in thin section looks like very small tiles forming over the quartz grain; if even higher temperatures are reached, silica glass can also form (in thin section these look like clear, round pools). A high-temperature mineral often seen in Chinese glazes at $\geq 1000^{\circ}\text{C}$ is anorthite, a calcium aluminum silicate mineral that frequently forms as an interaction product at the boundary between clay and a lime-rich glaze. However, fully understanding firing and cooling conditions is complicated, because the final appearance is the result of many variables, including mix of raw materials, maximum temperature attained, rate of temperature rise, rate of

cooling, total duration of firing, time maintained at peak temperature, and atmospheric conditions during firing (oxidizing, reducing, or a combination). Typically, thin-section petrography is one tool among many that are called upon in a study of ceramic firing and cooling regimes.

Thin sections provide a good view of decorative layers on a ceramic. Subtle evidence of burnishing or polishing to produce a more lustrous surface may be more visible in thin section than to the unaided eye. Fine particles, especially the platy clay and mica minerals, may show a clear parallel orientation that is due to surface burnishing, versus a more random orientation at greater depth into the ceramic material. Applied decorative layers can include slip, paint, glaze, or enamel layers. Petrographic thin sections can help identify the presence of a deliberately applied layer and the order in which multiple layers were applied. The thickness of layers can be measured (the average, and the minimum and maximum), which can provide clues as to similarities and differences in decorative technology among workshops.

Thin-section petrography is also helpful for studying the presence, distribution, and characteristics of interaction layers that may form as the clay body encounters a decorative layer. For example, the clay matrix often begins to melt at a body–glaze boundary region, forming new secondary minerals. In many Chinese and other Asian ceramics, a lime-rich glaze interacts with melting clay at the boundary area to form thin needles of anorthite. This layer of anorthite creates a white ground under the glaze, reflecting light back through the glaze and contributing to a lustrous quality. Bubbles created as gases are released by ceramic bodies and glazes at high temperatures often become trapped within the glaze. These, too, contribute to the reflective quality of many Asian glazes. Potters often deliberately determine the temperature, firing duration, and glaze viscosity in order to control the amount and size of bubbles so as to produce the specific surface effects desired. Thin-section petrography can clarify the range and variability of bubble sizes and their locations in the glaze layer, providing additional clues about the firing and glaze technology and the aesthetic intent of potters and kiln managers.

New directions and the continued power of petrography in ceramic analysis

Petrographic ceramic analysis is still a very active field of research. Some current work extends the methodology itself, for instance by adding high-resolution geological scanners and image analysis (Reedy 2008). Other work extends the type of materials characterized (e.g., volcanic ash temper, loess, microfossils, etc.) and the range of archeological and anthropological questions that are tackled (Quinn 2013; Ownby, Druc, and Masucci 2017). Often petrography, with its unique capabilities, is combined with other analytical methods to extract the maximum amount of information possible from a study of ceramic materials. By using all available tools, ceramic petrographers help resolve some of the fundamental questions in anthropology and archaeology.

SEE ALSO: Characterization of Ceramics;
Optical Microscopy

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Pigments and Binders

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Pigments and binders have been used since prehistory to paint colored layers. Over the centuries, artists started to develop specific recipes to improve their performance, in terms of both the aesthetic appearance and durability of their paintings.

Painters experimented with a multitude of materials as paint vehicles. Organic binders typically adhered to the ground layer and also provided a matrix capable of suspending the pigments. Specific binders were needed to form stable films with aesthetic properties, and can be divided into two main classes: inorganic and organic. The most famous inorganic binder is calcium carbonate, used in the *fresco* technique; however, lime techniques also fall within the category of paints achieved with inorganic binding media. Natural organic binders include proteinaceous, glycerolipid, and saccharide materials. Synthetic and semisynthetic organic binders are also widespread, as will be detailed in the following sections.

Frescoes

In frescoes, the binder is the product of a chemical process, resulting in a mechanical bonding of the pigment particles, as follows:

- The plaster is a water mixture of slaked lime and an aggregate ($\text{CaO} + \text{H}_2\text{O} \rightarrow \text{Ca(OH)}_2$).
- The plaster dries and acts as a ground layer, support, and binding agent, locking the pigment particles into place through the formation of calcium carbonate ($\text{Ca(OH)}_2 + \text{CO}_2 \rightarrow \text{CaCO}_3 + \text{H}_2\text{O}$).

Due to the high alkalinity of the substrate constituted by fresh plaster, only stable inorganic

pigments (such as green and red earths, Egyptian blue, San Giovanni white, hematite, goethite, lapis lazuli, ivory, and carbon black) dispersed in water are used in frescoes. Neither lakes nor organic pigments can be used in this technique due to the strongly alkaline conditions.

Proteinaceous paint binders

Proteinaceous paint binders, mainly egg, casein, or animal glue used as tempera, are polymeric materials made up of a specific sequence of amino acids dispersed in water and containing a small amount of lipids. Once applied onto the substrate with the pigments, the water contained in the raw material evaporates, leaving the polymeric structure to form the paint film. Protein-based binders are some of the most commonly used and the most durable (Colombini 2009, 237–259). Other proteinaceous binders were used in the West, such as garlic in gildings (Colombini 2009, 4–6, 237–239).

Glycerolipid binders

Binders for oil paints are generally prepared using siccative oils, such as linseed, walnut, or poppy seed oils in western countries and tung oil in the East. These oils are characterized by their high triglyceride content containing highly unsaturated acyl chains, for example, trilinolein in linseed oil. The pigments are dispersed in the medium, which, once applied on the substrate, starts to polymerize thanks to the action of light and atmospheric oxygen. Oxidation and polymerization reactions occur to form the paint film, as a result of the subsequent radical reactions (Colombini 2009, 191–213).

Oil binders have also been applied in mixtures with proteinaceous materials (generally egg) to obtain the so-called *tempera grassa*. This technique was used in the Renaissance and was rediscovered in the twentieth century. Technical

issues and the use of tempera were keenly debated among those artists involved in the renewal of the classicist style and traditional working methods. Consequently, numerous formulations containing proteinaceous binders were developed. Today, the term “tempera” is more related to the rheological properties of the paint, which are strongly influenced by minor additives (such as glycerol, soaps, or tallow) more than the main constituents (proteins and/or lipids).

Other lipid-based paint binders include natural waxes. Of these, beeswax was the most common, particularly to produce Punic wax (thought to have been the main ingredient in *encausto* paint). Waxes are hydrophobic substances made up of complex molecular mixtures containing various homologous compounds such as fatty acids, *n*-alkanes, *n*-alcohols, and esters in varying percentages depending on the origin of the material (Colombini 2009, 97–100).

Polysaccharide binders

The most common polysaccharide paint binders are natural gums. Plant gums are naturally occurring polysaccharide exudates from several species of plants or extracted from the endosperm of some seeds. The polymers consist of aldopentoses, aldohexoses, and uronic acids joined together by glycosidic bonds. Saccharide paint binders were used for several purposes, and watercolor painting, involving the use of Arabic gum, is one of the most famous (Bonaduce et al. 2016). However, saccharides have been found as paint materials in several archaeological contexts. As a painting material, this binder is one of the most labile, as it is subject to biodeterioration.

East Asian Asian lacquers

Lacquers are natural polymers that have been used as both varnishes and painting media since ancient times and consist of the sap extracted from trees growing in East Asia and Japan. Chinese, Korean, and Japanese lacquer trees (*Rhus verniciflua*) all contain urushiol as the monomeric unit, while Taiwanese and Vietnamese lacquer

trees (*Rhus succedanea*) contain laccol, and *Melanorrhoea usitata*. Thai and Burmese lacquer trees contain thitsiol. Minor components have been found in the polymeric structure of the lacquer, whose properties also depend on the recipe used for its production.

Semisynthetic paint binders

Natural binders were modified greatly over the course of the nineteenth century to meet the need for stable and fast-drying artist materials. The introduction of paint tubes forced manufacturers to use additives to improve the durability of their products. “Modern oils” were thus introduced, which contained not only siccativ but also semisiccativ and nonsiccativ oils (safflower, sunflower, palm, and castor oils). The tubes contained inorganic species (CaCO_3 , MgSO_4) to improve the texture, surfactants such as metal soaps, and pigments. Since the 1940s, natural oils have been modified to obtain alkyd paints/resins, which are oil-modified polyester paints prepared from natural oils and treated to improve their polymerization, by adding a polyol (trimethylolpropane, glycerine, or pentaerythritol) and dicarboxylic acids or anhydrides, such as phthalic anhydride or maleic anhydride. They are typically sold in tubes with the addition of pigments and several species to improve texture and durability (van den Berg 2014).

Synthetic binders

One simple way to describe synthetic binders is to classify them into two main groups: artists’ paints (mainly acrylic and oil), and house paints (usually alkyd and polyvinyl acetate) (Learner et al. 2008). The first, introduced in the late 1920s, was nitrocellulose house paint, followed by alkyd house paint in the 1930s, and polyvinylacetate (PVA) emulsion house paint in the 1940s. Artists’ acrylic solution paint followed in the late 1940s and acrylic emulsions in the mid-1950s.

The house paint polyvinyl acetate (PVA) entered the market at the same time as alkyd

paints, and was slightly modified by adding a plasticizer or copolymerization with a softer monomer to improve its performance.

Pigments

Pigments fall into two main categories: inorganic and organic. A pigment is a species that absorbs visible light. This is due to either the transition elements, found in inorganic pigments, or the delocalization of the electrons in conjugated unsaturated systems in organic pigments. Given that pigments are insoluble in the medium, organic pigments are often obtained by complexation or adsorption on an inorganic, uncolored salt. Organic pigments obtained by complexation or adsorption are generally called pigment lakes. If the organic species is insoluble in the medium, or, being strongly acid or alkaline, is precipitated as a salt, it can be referred to as an organic pigment. Some examples of the most commonly used pigments are listed in Table 1.

In the past, the pigments available to artists were very limited, and some, such as ultramarine blue, were so expensive that they were only used for precious decorations. Manufacturers of artists' paints currently produce a very large variety of pigments in paint tubes, mainly of an organic nature. These modern pigments have a uniform particle size, are compatible with oil or synthetic binders, and are reasonably resistant to environmental conditions.

Characterization of pigments and binders

Characterizing the pigments and the binding media in a work of art is challenging for chemists and physicists. The most common techniques for inorganic species are those based on elemental analysis, in particular X-ray fluorescence (XRF), and electronic spectroscopy, such as fiber optic reflectance spectroscopy. These techniques can be used both nondestructively and noninvasively on the painting. Another common technique is scanning electron microscopy energy dispersive X-ray analysis (SEM-EDX) applied on samples in thin and cross-sections. To provide more detailed information on the molecular structure

of the pigments, Fourier transform infrared spectroscopy (FTIR) or Raman spectroscopy are the most common techniques.

FTIR and Raman spectroscopy can provide information on organic pigments and binders, but being bulk methods, both techniques suffer from matrix effects. More extensive information can only be obtained by applying microdestructive techniques, such as chromatography and mass spectrometry (MS). The separating power of liquid chromatography (LC) and gas chromatography (GC), coupled with the specificity and sensitivity of MS detection, often lead to the unambiguous identification of the binding medium, even in extremely aged and degraded samples, and of organic pigments (Colombini et al. 2010; Bonaduce et al. 2016; Degano and La Nasa 2016). The application of proteomics is a particular example, which may lead to binder identification when ambiguous characterizations are obtained with GC/MS techniques.

Finally, to establish the spatial distribution of the organic and inorganic materials identified, synchrotron radiation FTIR (SR micro-FTIR) and SR XRF and X-ray diffraction (XRD) can be used to collect high-contrast chemical images which are fundamental in defining the painting technique (Bertrand, Dillmann, and Reiche 2015).

Determining both pigments and binders leads to a comprehensive characterization of the painting from a chemical point of view. Good examples of comprehensive examination of the constituting materials include the study of western painting techniques and the characterization of the organic media in the wall paintings of the "Palace of Nestor" at Pylos, Greece, which show evidence of a *secco* painting technique in the Bronze Age (Brecoulaki et al. 2012). In addition, in eastern countries, the determination of the organic materials in the Five Northern Provinces' Assembly Hall revealed the technique of the Qing dynasty painters in civil buildings (Lluveras-Tenorio et al. 2015).

SEE ALSO: Archaeometry; Characterization of Pigments; Chemistry in Archaeology; Chromatographic Techniques in Conservation; Chromatography and Archaeological Materials Analysis; Dyes; Electron Microscopy in Conservation; Gas Chromatography–Mass Spectrometry (GC-MS); High Performance

Table 1 Examples of the most commonly used pigments.

<i>Name of pigment</i>	<i>Color</i>	<i>Formula/chemical class</i>	<i>Notes</i>
Lead white	White	$2\text{PbCO}_3 \cdot \text{Pb}(\text{OH})_2$	Most commonly used white until the nineteenth century
Lime white (San Giovanni white)	White	CaCO_3	Mostly in wall paintings
Titanium dioxide	White	TiO_2	Synthetic (1920)
Gypsum	White	$\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$	Mostly used for ground layers
Azurite	Blue	$2\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$	Very precious
Ultramarine blue (lazurite)	Blue	$(\text{Mg}, \text{Fe}^{2+})\text{Al}_2(\text{PO}_4)_2(\text{OH})_2$	
Smalt (cobalt glass)	Blue	Obtained by including cobalt oxides in a glass melt and grinding the final product	Mostly used in the seventeenth–eighteenth centuries
Indigo	Blue	Organic, natural	Used in America
Maya blue	Blue	Indigo adsorbed on clay	
Malachite	Green	$\text{CuCO}_3 \cdot \text{Cu}(\text{OH})_2$	Synthesized by Greek and Roman painters
Verdigris (copper acetate)	Green	$\text{Cu}(\text{CH}_3\text{COO})_2 \cdot 2\text{Cu}(\text{OH})_2$	
Phthalo green	Green	Copper phthalocyanine	
Yellow and red ocher	Yellow-red	Fe_2O_3 (from yellow to red depending on the hydration)	Very stable, synthetic (1936)
Lead chromate	Yellow	PbCrO_4	
Red lead (minium)	Red	Pb_3O_4	Commercially available since 1818
Vermilion/cinnabar	Red	HgS	
Madder lake	Red	Vegetal anthraquinones precipitated as a complex with alum	Lake from ancient times
Carmine	Red	Animal anthraquinones (carminic acid mainly) precipitated as a salt	Very precious, seventeenth century
Eosin	Pink-fuchsia	Organic pigment (xanthene class)	Synthetic, very fugitive
Ivory black	Black	Amorphous carbon obtained from ivory and animal bones, also containing calcium phosphate and carbonate	
Carbon black/vine black	Black	Amorphous carbon obtained from organic material	

Liquid Chromatography (HPLC); Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Mass Spectrometry (MS); Polymers in Conservation; Raman Spectroscopy and Material Analysis

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PIXE and Material Analysis

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Material analysis for archaeology

Archaeological objects and materials are a primary source of knowledge about the societies of the past, the exploitation of sources of raw materials, the technology and manufacturing techniques of objects, exchange routes and trade, chronological data, and deterioration. For this reason, it is very important to apply a suitable set and sequence of techniques for characterization of materials. Imaging techniques provide a global examination of objects at macro- and microscopic levels to select specific areas for non-invasive methods, such as spectroscopic techniques for in-situ and laboratory analyses (X-ray fluorescence, Raman and Fourier transform infrared spectroscopies, ion beam analysis). After these analyses, and depending on the archaeological questions and the kind of material studied, sampling may be considered for microanalysis using methods of optical and electron microscopy techniques, spectroscopies and chromatographies.

From the 1990s and during the first decade of the 2000s, there was a rapid development of ion beam analytical methods for heritage and archaeology. Several methods were improved, new instrumentation was developed, and specialized laboratories and groups were implemented worldwide. In particular, particle induced X-ray emission spectroscopy (PIXE) and Rutherford backscattering spectrometry (RBS), complemented by particle induced gamma-ray emission spectroscopy (PIGE), provide a unique analytical tool when an ion beam accelerator is available. Often, the combined use of elemental analysis with other techniques is necessary for a complete and correct interpretation of the data. PIXE can be successfully applied to practically all kinds of

inorganic materials and objects from the archaeological record: pottery, stone objects (obsidian, flints, jade), gems, metallic artifacts, glaze, glass, bone and teeth, manuscripts and paintings.

PIXE and other ion beam methods

PIXE is based on the interaction between a monoenergetic positive ion beam, mainly hydrogen (proton) or helium (alpha particle) ions, and the electrons of the atoms of materials. These ions have enough energy to cross the electronic clouds and to eject electrons from the inner electronic shells. Atoms are ionized, and to recover their natural energy state, electrons from outer shells undergo transitions in order to fill the holes left by the ejected electrons in the inner shells. These transitions are accompanied by emission of energy, as X-rays, with specific energies that correspond to the energy gap between the electron shells (see Figure 1). The energies and intensities of emitted X-rays are characteristic of the chemical elements and the elemental concentrations in the material.

Certain electron transitions will emit energy in the range of ultraviolet to infrared light. This light emission is characteristic of the material and its elemental impurities. The technique that captures this effect is called ion beam induced luminescence (IBIL) or ionoluminescence (IOL).

Other secondary emissions are simultaneously produced by Coulombian repulsion between the nucleus and positive ions: the ion beam can be scattered, and the change in the energy of the scattered ions is specific for each kind of atom. This is the physical principle of Rutherford backscattering spectrometry (RBS), which is useful for measuring the composition of the light elements and the elemental depth profile.

If the ion beam energy is high enough to overcome the nuclear repulsion, the ions can reach the nucleus and reactions take place, emitting particles and gamma rays of characteristic energies that are specific for each atom. This effect

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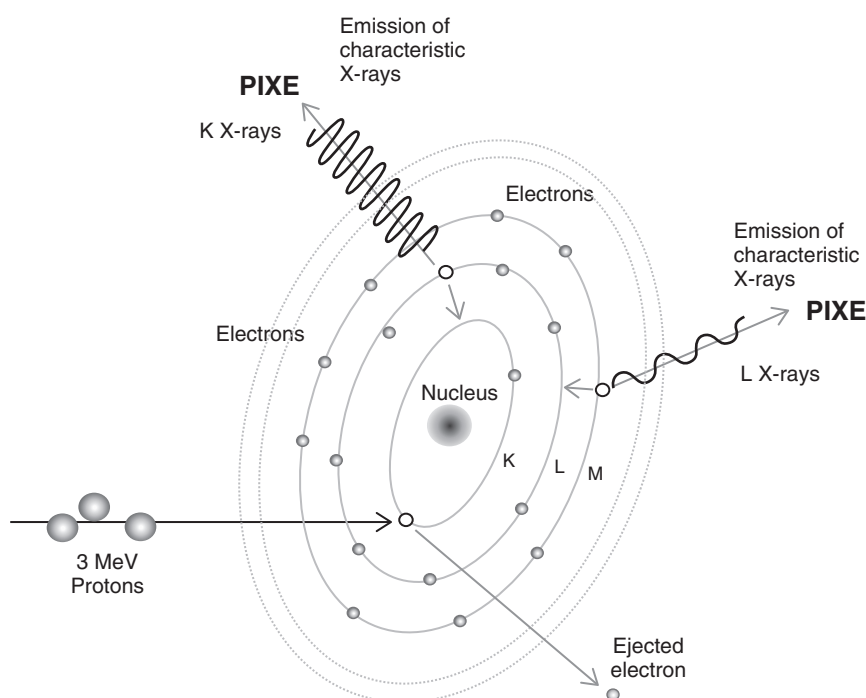


Figure 1 Ion beam interaction with the atom to induce characteristic X-ray emissions.

is more likely for light elements (such as fluorine and sodium), and it is the principle of particle induced gamma-ray emission spectroscopy (PIGE).

Since all these phenomena occur simultaneously, modern ion beam analysis involves the detection of all the secondary emissions (Beck et al. 2011). Characteristic X-ray emission is the most probable phenomenon, and for this reason PIXE is the most used and versatile ion beam technique.

Experimental setup and analytical capabilities

For archaeological applications, external beams are the most appropriate systems because it is possible to analyze the object directly in a non-invasive way without any preparation. This is also valid for fragments or samples.

In this device, the proton beam from an accelerator beam line under vacuum crosses a window of a polymer, aluminum or silicon. The beam spreads as it traverses the atmosphere. The proton

beam is collimated to determine the analyzed area, typically 1–2 mm diameter, but it can range from 0.25–4 mm depending on the purpose of the analysis. If the object is set in front of the beam at a short distance (5–10 mm), the ion beam impinges the object surface with enough energy to induce characteristic X-rays for PIXE analysis. X-ray detectors, typically two, collect the characteristic X-rays emitted by the elements of the material (see Figure 2). Usually, one detector is dedicated to light element detection using a helium jet in the path between the object surface and the detector. This system improves the detection of elements from sodium to iron. Another detector provided with a filter reduces the collection of X-rays of light and major elements in order to detect heavier elements as well as trace elements of the material (Sokaras et al. 2011). The proton beam energy ranges from 2–3 MeV, when the detection limits are the highest for PIXE (some $\mu\text{g/g}$). PIXE measurements take a few minutes per analyzed region.

Other detectors for gamma-rays, scattered protons and light can be set in the external beam device in order to carry out simultaneous PIGE,



Figure 2 External beam setup of the Pelletron Accelerator of Instituto de Fisica, UNAM, during the analysis of a Mayan mask.

RBS, and IBIL. In particular, RBS allows the measurement of light element concentrations, which are significant for matrix corrections, by X-ray absorption, and helps to determine the elemental depth profile. PIXE data prove to be more accurate when light element concentrations are measured.

The analyzed depth depends on the beam energy and on the X-ray absorption for each element in the material. The X-rays of light elements (of lower energy) are more absorbed than the X-rays of heavier elements (of higher energy). Typically, for materials composed of heavier elements (such as metals), the analyzed depth is less than $30\text{ }\mu\text{m}$. For lighter materials (like pottery) the analyzed depth may reach $100\text{ }\mu\text{m}$ for the heavier elements. The analyzed depth is less than the depth reached by the proton beam within the material.

Standard reference materials (SRMs) from NIST or IAEA must be measured under the same experimental conditions. This is necessary to

calibrate the PIXE system and to measure the detection efficiency for X-rays. Some specific SRMs are available for sediments (also useful for pottery), metals (e.g., gold, silver, bronze, and brass), obsidian, glass, and bone, among others.

X-ray intensities are measured from PIXE spectra and calculations are performed considering the beam energy, the geometry of the experimental device, and experimental data from reference materials, in order to measure the elemental composition (wt.%). Several codes, such as GUPIX, have been developed to carry out rapid quantitative analyses.

Since the analyzed depth is determined by the ion beam energy, by modifying the beam energy gradually, it is possible to reach different depths. PIXE spectra will change depending on the layered structure and its composition. Using this method, called differential PIXE, it is possible to measure the elemental depth profile (Calligaro, Gonzalez, and Pichon 2015). This procedure has been developed for technological studies of

metals and pictorial techniques of paintings from the Italian Renaissance. This capability makes PIXE and RBS a unique non-destructive tool to measure the elemental depth profile.

When microanalysis is required, it is possible to produce maps of elemental distribution with a spatial resolution of less than 5 μm under a vacuum, using microprobes with quadrupole optics to focus and scan the beam within 1 mm^2 . Using external microbeams it is also possible to carry out micromapping, but with a lower spatial resolution (30 μm). This analysis is suitable for heterogeneous materials such as minerals and paint layers.

Limitations

Several limitations exist for PIXE. First, objects must be transported to the laboratory. This is not a problem for some samples, but it may be a difficulty for precious objects considering transportation, insurance, storage, handling, and conservation conditions in the laboratory.

To solve this problem, it is possible to perform PIXE using a portable spectrometer with radioactive sources of alpha particles of 5 MeV (Pappalardo et al. 2015). A PIXE spectrum is collected over one hour (depending on the activity of the source); this is an in situ non-invasive method that has been applied to pottery, metallic artifacts, and manuscripts.

Analyzed depth by PIXE also has some limitations due to the X-ray absorption in the materials. This is important for objects composed of layers like paintings and for patinas or plating of metallic artifacts. Analytical information may be limited to the most external layers, depending on their composition and thicknesses, as well as the manufacturing or pictorial techniques.

Ion beam irradiation of some materials can produce dark spots due to defects in the material (e.g., turquoise or glass). Nevertheless, it has been observed that these spots may disappear after some time or under ultraviolet light, recovering its original aspect.

Finally, PIXE is mainly a technique for inorganic material analysis, although it is possible to

study organic materials in some cases, such as amber from its inorganic inclusions.

Applications

Pottery

Ceramics is one of the most abundant materials in the archaeological record. Pottery is made from several clays and temper with slip coatings and pigments at the surface. Elemental analysis of pottery can be used to determine major, minor, and trace elements of the ceramic components. This information is useful for determining the provenance of raw materials, identifying pigments, and studying the manufacture of the pottery.

Ceramic objects and sherds can be analyzed directly with external beams to determine the elemental composition of the ceramic paste, slipware, and pigments. This can be used for homogeneous ceramics, such as Chinese porcelain.

For accurate measurements of heterogeneous paste, the surface of the sherds is eliminated mechanically to take out the painted surfaces, slipware, and surfaces altered by the archaeological context. A small clean fragment is powdered and heated to dry the material and to eliminate organic materials. Homogeneous pellets are prepared with a hydraulic press. Pellets are then irradiated for few minutes to get suitable PIXE spectra. In this way, it is possible to avoid texture and heterogeneity effects of the paste.

After quantitative analyses, elemental concentration data are processed by statistical means such as cluster and factor analysis to determine groups of similar composition. Clusters may be contrasted and interpreted to determine changes in the exploitation of raw materials, to identify local and foreign manufacturing, as well as exchange and trade.

Obsidian and glass

Obsidian is a natural homogeneous volcanic glass. It has been used as a cutting tool and to produce artifacts for offerings. Elemental analysis by PIXE and PIGE has proven to be a powerful method to measure directly the

elemental composition of the artifacts, without any sampling or preparation. Data are useful for sourcing of pieces and to research trade and exchange between different regions. Light elements (e.g., sodium) from PIGE analysis are often important to contrast the material composition. The PIXE-PIGE method has been successfully used for the provenance of obsidians from Mesoamerica and South America, the Mediterranean region, and Oceania.

On the other hand, glass production can be inferred from elemental data, including impurities and trace elements. It is possible to classify glass from the contents of calcium, potassium, and sodium, and to determine exchange and trade. This has been done for glass from ancient Egypt, Roman glass, Byzantine and Islamic tesserae, Renaissance glass from Venice, and medieval stained glass, among other studies (Neri et al. 2016).

Glazed pottery has been extensively studied to determine the composition and technology of the glaze and the pigments. Glazed potsherds and tiles from Spain from the fourteenth to eighteenth centuries were analyzed by PIXE and other methods to understand the evolution of raw materials and manufacturing techniques. From this research, a change in the microstructure was observed from the fifteenth century, while the use of tin in glaze started from the seventeenth century. Other studies of glazed pottery from Italy, Portugal, Egypt and the Islamic world have revealed the composition of green, blue, black, and yellow colors. Surface analyses using PIXE, RBS, and PIGE have contributed to the understanding of the optical properties of glaze to produce a golden luster effect.

Gems and semiprecious stones

Following a similar approach for glass and obsidian, artifacts made with gemstones and precious minerals can be analyzed directly, in particular when the material is homogeneous. This is the case for emeralds, sapphires, and rubies. This approach has been applied to study the exploitation of beds of gems from Asia and Africa, and trade routes to Mediterranean areas and Europe in different historical periods.

Some stones may be heterogeneous; in this case, the use of microbeams for PIXE and IBIL measurements is a suitable analytical strategy to characterize the mineral components of the surface. Jade from Mesoamerica and China, as well as lapis lazuli, has been studied in this way to investigate the provenance of raw materials (Re et al. 2011).

Metallic artifacts

Precious metals are usually well preserved with practically no surface corrosion, but they may have intentional patinas or surface enrichment to change their aspect. Also, metallic artifacts may be melted to produce other artifacts, and the alloys are often mixed. For copper-based alloys, like bronze, the artifacts have patinas or they may be gilded or silvered. Corrosion may be present and may interfere with the examination of the artifacts.

PIXE and RBS are suitable methods to determine the composition of the alloys and soldering procedures (Zucchiatti et al. 2014). Plating, gilding, and patination can be studied using differential PIXE since the metallic surface comprises layers of different compositions. These methods have been applied to artifacts from various historical periods in Europe, Iran, India, Mesoamerica, and Colombia. Also, the surface enrichment of coins has been studied to understand the economic development of various societies.

Despite the problem of remelting, sourcing of precious metals has been successfully determined by PIXE and other methods to establish the circulation and production of coins and other artifacts.

Microbeams have been used to characterize surface treatments and plating of metallic threads in historical textiles. These analyses have been carried out on samples under vacuum as well as directly on objects using external beams.

Manuscripts

Documents and ancient books have been studied by the analysis of inks, paper, and decorations. In particular, manuscripts from Europe and Asia have been effectively examined by PIXE with external beams to determine the materials used

to write and decorate the manuscripts, modifications and writing chronologies, and the printing procedures for books.

Paintings

The main difficulties for painting studies are the handling of the artworks, experimental conditions to avoid damage, and the analyzed depth limits (Calligaro et al. 2015). For small paintings, external beams and microbeams are suitable to characterize pigments at the surface. If the paint layers are not too thick (less than 30 μm), differential PIXE can provide insights into the sequence of layers and their composition.

Several studies on painting fragments and samples have been carried out for mural paintings and pigments. Examinations provide proper identification of inorganic pigments, but also pigment sources can be discriminated using PIXE.

Other materials

Bone remains are important materials for archaeological purposes, and can be used, for example, in palaeodiet studies by using iron, zinc, strontium, and barium contents in long bones. Teeth and hair may provide information about health and exposure to lead and other contaminants. PIXE is also suitable for discriminating between bone, ivory, and antler, by using the contents of calcium, magnesium, fluorine, and strontium.

Diagenesis can also be characterized by PIXE. This information is important for selecting samples for dating and conservation.

SEE ALSO: Archaeomineralogy; Bones and Ivory; Cements, Mortars, Binders; Characterization of Ceramics; Characterization of Metals and Alloys; Characterization of Pigments; Chemical Mapping; Chert, Silex, and Obsidian Sourcing; Cluster Analysis; Elemental Analysis of Pottery; Factor Analysis; Gemstones; Glass and Faience; Glass Color; Glazes, Slips, and Paints; Ion Beam Analysis (PIXE/RBS); Nondestructive Compositional Analysis of Ceramics; Portable X-Ray Fluorescence

Spectrometry (pXRF); X-Ray Fluorescence Spectrometry (XRF)

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Pyrotechnology of Cements

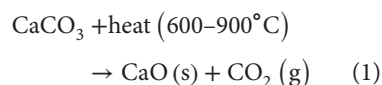
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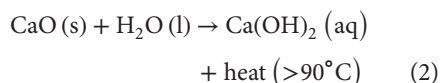
Beginning with the ancients, humans have been using different types of cements to improve construction techniques and building habitability. The initially used natural binders of rammed earth, clay, and tar later gave way to the application of pyrotechnology to limestone and gypsum which are heated to below melting point temperatures to improve their quality and durability. The resulting cements, which revolutionized construction in ancient societies, are still in use today.

Mortar and plaster are pyrotechnological outputs whose raw materials are quarried from carbonate rock and gypsum outcrops and must be heated to obtain the end product. When gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) is heated between 100 and 150 °C it loses part of its molecular water and forms the hemihydrate ($\text{CaSO}_4 \cdot 1/2\text{H}_2\text{O}$), and if the temperature reaches 250 °C, it totally loses the molecular water and anhydrite (CaSO_4) formation occurs. When water is added to these finely milled products they are rehydrated, and moldable paste with high workability forms. These gypsum mortars (known as Plaster of Paris) were the first in history to be used in wall coatings due to their low firing temperature (Carran et al. 2012).

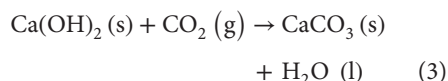
Since ancient times, one of the most widely used pyrotechnological cements has been lime. Lime mortars have four constituent raw materials: binder, aggregates, additives, and water. The binder is obtained from carbonate rock (CaCO_3 , limestone and dolomite), crushed and heated to temperatures of 600–900 °C to remove the CO_2 from the calcium or dolomitic carbonate. Known as calcination, the process yields calcium oxide (CaO), that is, quick or burnt lime:



Quick lime is then hydrated or slaked with water, an exothermal reaction ($>90^\circ\text{C}$) that forms calcium hydroxide (portlandite), a hydrated lime powder or slaked lime paste:



Over time, as this calcium hydroxide reacts with atmospheric CO_2 , it converts to calcium carbonate (CaCO_3) (equation (3)). Depending on environmental conditions, the CaCO_3 can precipitate as several polymorphs, evolving from the least to the most stable (vaterite, aragonite, and calcite, respectively). Calcite, the end product of what is known as carbonation and the form extant in lime mortar, has the same chemical composition as the original rock.



In other words, lime mortar pyrotechnology can be divided into three stages—calcination, hydration, and carbonation—which over time yield a compact, highly deterioration-resistant material.

Aerial lime carbonates in the absence of moisture. Such hydraulicity was attained by adding pozzolans, silica- and alumina-high compounds that react with lime in the presence of water or high humidity to form calcium silicate (CSH), calcium aluminate (CAH), and calcium aluminosilicate (CASH) hydrates. The result is a stable, mechanically strong binder that adheres firmly to the aggregate. Hydraulic lime, which already contains those hydrates itself, sets in the presence of water. Its discovery by John Smeaton in 1756 revolutionized ancient construction technology, for it could be used in moist environments or even underwater, to the benefit of civil works such as aqueducts, bridges, vats, ports, and roads across marshes (Elsen, Van Balen, and Mertens

2012). Hydraulic limes were classified by Luis Vicat as “feebly,” “moderately,” and “eminently” hydraulic, depending on the clay impurity content. For coatings and grouts, sometimes a lime–gypsum mixture is used to improve their setting.

Different ancient societies produced lime using local natural resources and by applying autochthonous technology, subsequently relayed across trade routes and via conquest and colonization. Pyrotechnology continued to evolve in historic times, driving the development of new materials, such as Portland cement in the nineteenth century. The archaeological study of these materials is of great interest, for it sheds light on the technological and trade-related evolution of many societies.

The earliest findings on pyrotechnology products came from Anatolia in Göbeklitepe (tenth to ninth millennium BCE) as lime and as gypsum and marl coatings on rammed earth walls in Çatalhöyük (6000–7500 BCE) (Schmidt, Hurd, and Thompson 2011; Mellaart 1967). The technology appeared later with lime use with organic additives in ancient China beginning at about 1000 BCE. In Europe, lime mortar was not extensively used until it was adopted by the Greeks and later by the Romans around the first millennium BCE. It was developed more after around 500 BCE when the Greeks improved aerial lime by adding pozzolans from the Santorini volcanic area (Ritzouli, Stefanidou, and Konopisi 2016). It was widely used as a mortar and concrete by the Imperial Romans, who prepared it initially with volcanic ash from the Pozzuoli region near Mount Vesuvius (Carran et al. 2012). With the fall of the Roman Empire, the use of mortar in western medieval Europe declined. A less-meticulous selection of materials yielded products of lower quality than Roman concrete. Roman tradition was kept alive in eastern Europe, however, by the Byzantines and later the Ottomans.

Roman cement, contrary to its ambiguous name, or so-called natural cement was discovered by James Parker and started to be used in 1796 in England. Natural cement whose advantage was its fast setting (less than 12 h) was manufactured from marly limestone (25–40% clay). Calcination lasted between 8 and 20 h at a temperature of 800–1200 °C (Varas, Alvarez de Buergo, and Fort 2005).

These cements were quickly replaced by Portland cement, whose industrial production began in 1845 in England with Isaac Johnson, after Joseph Aspdin’s patent in 1824. Its raw material was pure limestone (80–75%) and clay (20–25%), calcined at temperatures above 1300 °C, which allowed a shorter setting time, at least 8 h.

Both types of cement are differentiated by their mineralogy, since in natural cement, belite (dicalcium silicate, C_2S) is the main phase which gives late strength, while in Portland cement, the main phase is alite (tricalcium silicate, C_3S) which gives early strength. The calcination process of natural cement is carried out in vertical kilns, as so the lime mortars, but an innovation with Portland cement is the use of subhorizontal rotary kilns in which the temperature increases from the entrance to the exit, reaching between 1350 and 1450 °C, where the components melt. When cooled, clinker is obtained. This product consists of 60 percent tricalcium silicate ($3CaO \cdot SiO_2$, C_3S), 20–30 percent dicalcium silicate ($2CaO \cdot SiO_2$, C_2S), 7–14 percent tricalcium aluminate ($3CaO \cdot Al_2O_3$, C_3A), and 2–12 percent tetracalcium ferroaluminate ($4CaO \cdot Al_2O_3 \cdot Fe_2O_3$, C_4AF). Finally, to improve its qualities, a small percentage of gypsum and additives (ash, slag, etc.) are added. The obtained binder is mixed with aggregates of different size and composition and water to form an applicable paste. With the reaction with water, calcium silicates (C_2S , C_3S) hydrate and cause the formation of tobermorite ($Ca_5Si_6O_{16}(OH)_2 \cdot 5H_2O$, CSH); likewise, in the presence of gypsum, calcium hydroxide and tricalcium aluminates (C_3A) favor the formation of ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O$).

Deploying analytical techniques to determine the type of limes used in the built heritage, archaeologists can establish construction periods and relative dating of the various parts of a building. Macroscopic characterization provides organoleptic information; however, it does not suffice to type mortars. Physical–chemical analyses must be conducted to confirm the type of mortars.

Polarized light microscope-based petrographic studies of thin mortar sections reveal the composition and form of the aggregates and their particle size distribution. This method can be

used to examine the interface between the mortar and adjacent materials, identify binder type, aggregates, clinker nodules, and lime lumps, and determine the percentage of pores and the presence of new mineral phases generated during carbonation. It also delivers an estimate of the binder:aggregate ratio.

X-ray diffraction (XRD) is a technique particularly apt for determining the nature of binder and aggregate composition after the two components are separated. It is limited inasmuch as it cannot identify amorphous or noncrystalline mineral phases or any with a content of less than 5 percent, or differentiate between carbonated binder and limestone aggregate.

In contrast, based on crystal habit, scanning electron microscopy (SEM), together with energy dispersive X-ray analysis (EDX), can distinguish the carbonate mineral phase formed from any remaining noncarbonated portlandite crystals. It also determines elemental chemical composition, which is important to establish the size and shape of the crystals of hydraulic phases which have direct impact on the mortar's quality. Since carbonation takes place gradually from the surface inward, SEM can also be used to establish the depth of the carbonation. Phenolphthalein ($C_{20}H_{14}O_4$), another reliable indicator of carbonation, detects the presence of portlandite by dyeing the respective area pink, whereas no color change in the mortar denotes full carbonation.

Thermogravimetry differential thermal analysis (TG-DTA) is yet another indispensable technique for determining mortar hydraulicity. It measures sample weight loss with rising temperature due to the loss of water and CO_2 attendant upon the decomposition of $CaCO_3$ in the mortar.

Weight loss at temperatures of under $120^\circ C$ is attributed to hygroscopic water in the mortar and loss at $200\text{--}600^\circ C$ primarily to bound water in hydraulic compounds (CSH, CASH, and similar). Weight loss at over $600^\circ C$ is the outcome of $CaCO_3$ decomposition (Moropolou, Bakolas, and Bisbikou 2000). The $CO_2:H_2O$ ratio provides a measure of mortar hydraulicity. The higher the ratio, the lower the hydraulicity.

XRF and inductively coupled plasma mass spectroscopy (ICP-MS) can be used to determine the percentage of each mortar constituent, as

well as the cementation index (CI) described by L. Vicat and the hydraulicity index (HI) later proposed by E. C. Eckel:

$$CI = \frac{2.8SiO_2 + 1.1Al_2O_3 + 0.7Fe_2O_3}{CaO + 1.4MgO} \quad (4)$$

$$HI = \frac{SiO_2 + Al_2O}{CaO} \quad (5)$$

Lime mortar/cement can be characterized mineralogically and chemically by the techniques mentioned above to determine the degree of carbonation and type of lime used. Other tests can characterize the petrophysical properties of mortars by determining compactness, effective porosity, pore size distribution, and air permeability. These, together with ultrasound wave velocity and surface hardness tests, are instrumental in defining the degree of deterioration of the mortars studied. Besides, being nondestructive, some can be conducted at the archaeological site itself, with no need to take samples.

Portland cement was often used in archaeological and architectural heritage restoration, because it was cost efficient as it took less time to set, and it dominated the market; however, it has been revealed that it can cause damage due to its higher rigidity and impermeability, and it can generate very harmful salt phases. Moreover, alkali minerals in these cements decrease the durability and may lead to expansive compounds which favor the corrosion of metallic elements in humid environments. Under these circumstances, identification/differentiation of the cement and mortar is necessary to rescue the damaged heritage.

SEE ALSO: Cements, Mortars, Binders; Deterioration; Optical Microscopy; Petrography and Ceramics; Portable X-Ray Fluorescence Spectrometry (pXRF); Raman Spectroscopy and Material Analysis; Volcanic Rock Sourcing

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Raman Spectroscopy and Material Analysis

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Nondestructive analysis on heritage materials

Not only is the detailed characterization of the constituents of heritage objects important for understanding the material and technological knowledge behind its manufacturing, but also the materials used can act as both a chronological or geographical marker—and help establish the adequate policies and procedures for its restoration and conservation. To fulfill such a goal, many analytical techniques have been applied, with the combination of several techniques being the most useful approach. The methodologies have evolved from classical analytical chemistry methods, such as high-performance liquid chromatography (HPLC) and gas chromatography mass spectroscopy (GC-MS), to the preference for nondestructive techniques, which can be complemented with destructive analysis on selected samples. Technological advances have led to the miniaturization and portability of spectrometers, allowing in-situ analysis to be carried out in many cases.

A combination of imaging and spectroscopic analysis is usually preferred in order to retrieve as much information as possible from the studied object. A general inspection through imaging techniques may include visible, infrared, and ultraviolet light imaging, false-color infrared imaging, and multispectral imaging. The most common combination of spectroscopic techniques comprises elemental analysis with X-ray fluorescence (XRF), scanning electron microscopy energy dispersive X-ray spectroscopy (SEM-EDX), and particle induced X-ray and gamma-ray emission (PIXE and PIGE); structural techniques, mainly X-ray diffraction (XRD); and both organic and inorganic compound

analysis using fiber optic reflectance spectroscopy (FORS), visible light fluorescence spectroscopy, Fourier transform infrared spectroscopy (FTIR) and Raman spectroscopy.

The Raman effect

The Raman effect was first reported by C. V. Raman and K. S. Krishnan in 1928 (Raman and Krishnan 1928) and, later that year, by G. Landsberg and L. Mandelstam (Landsberg and Mandelstam 1928). Raman was awarded with the Nobel Prize in Physics in 1930 “for his work on the scattering of light and for the discovery of the Raman effect.” The effect consists of the inelastic dispersion of a photon by an electron in a molecular bond. When light is dispersed by an atom or molecule, most of the photons undergo an elastic dispersion—that is, the dispersed photon has the same frequency and energy as the incident photon—known as Rayleigh dispersion. Around one in ten million incident photons suffer inelastic dispersion, providing it with a different energy than the incident photon. The dispersed radiation gives information about the composition of the studied object, since its shift in frequency—known as Raman shift—is related to the type of bonds and the electronic environment where the interacting electron is located. Thus, the resulting spectrum can be considered a vibrational signature of the molecule (Vandenabeele 2013).

There are two possibilities when the Raman effect occurs, as the photon can be dispersed with a lower or higher energy than the incident one (Figure 1). Such phenomena are known as Stokes and anti-Stokes dispersion, respectively. In Stokes dispersion, the incident photon interacts with an electron located on the ground vibrational level, which absorbs all of the energy from the photon and reaches a higher, excited energy level. For the electron to return to a more stable state at a lower energy, the molecule releases a photon with an energy equal to the difference between the excited level and the first vibrational level, where the electron is finally at

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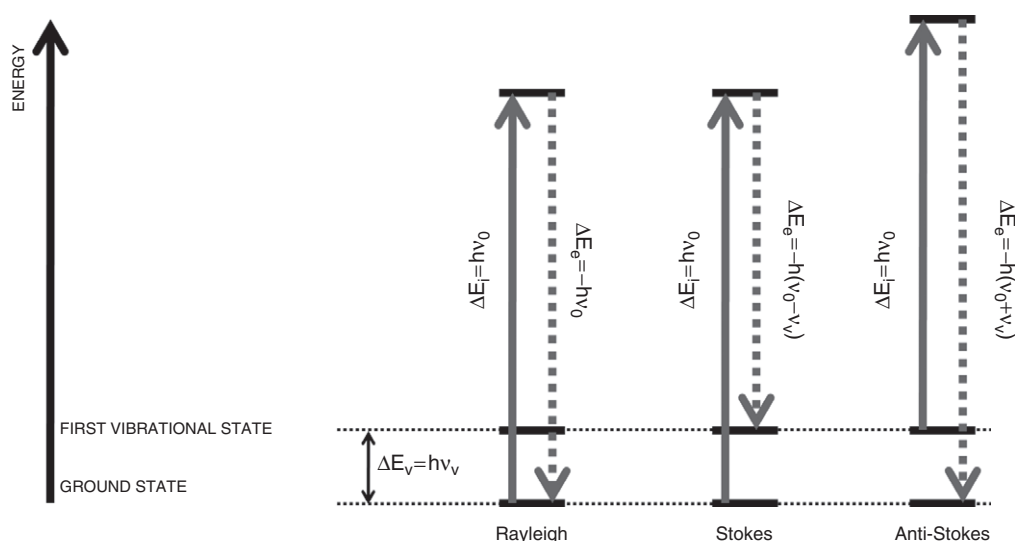


Figure 1 Vibrational transitions associated with the Raman effect.

rest. On the contrary, for anti-Stokes dispersion to take place the incident photon must interact with an electron located on the first vibrational state. The electron reaches an excited state and the molecule returns to a stable configuration by releasing a photon with an energy equal to the difference between the excited and ground states, which is higher than the energy of the incident photon. At room temperature, only 1 percent of the electrons are on the first vibrational state, so the Stokes dispersion is 100 times more probable—and intense—than the anti-Stokes and is most commonly employed for Raman spectroscopy.

Instrumentation

The basic components of a Raman spectrometer are a laser source, a system for illuminating the sample, and a suitable detector (a spectrometer or spectral analyzer). Such instruments must eliminate the very strong signal from the Rayleigh dispersion and detect the bands that correspond to the Stokes—or anti-Stokes—dispersion. The most common laser wavelengths used are 532 and 785 nm, but 485, 514, 633, and 1,064 nm are also utilized. The analysis area ranges from 1 to 5 mm, without the use of a microscope, to a few micrometers for microscope-coupled benchtop spectrometers.

Raman spectrometers' size ranges from small handheld instruments to benchtop equipment. Handheld analyzers are often very light, easy to use, and designed for specific applications, usually for the identification of raw materials in industry and for the detection of drugs and explosives. More complex analysis, involving unknown materials—or materials that are not included in the equipment's database—can be difficult to perform.

A second category of portable spectrometers comprises instruments weighting around 2–5 kg. They can be used both in the laboratory and in situ; a microscope can be mounted on these instruments or come already equipped with a built-in microscope, and they are usually suitable for analyzing liquid and solid samples. Although their performance cannot be compared with benchtop instruments, portable spectrometers successfully answer a wide range of investigative questions.

Benchtop spectrometers constitute the third category. Among their capabilities are the high sensitivity and spectral resolution, the inclusion of powerful microscopes, and multiple laser wavelengths. Many of them can be coupled to external fiber optic probes for the analysis of large objects. In most cases, the studies must be performed on small samples, but this disadvantage is compensated by the quality of the information that can be gathered.

Limitations and alternatives

Raman spectroscopy faces two important limitations. As the Raman effect has a low probability to occur, Raman signals are often weak and difficult to observe. This can be overcome by increasing the laser power, the acquisition time, or both, but both solutions also increase the chance of damaging the analyzed object due to the amount of energy deposited in the analyzed area by the laser. A second drawback is the interference of fluorescence caused by the laser on a wide variety of substances, mainly organic compounds. The intensity of this fluorescence background can even prevent the observation of the Raman bands from the object (Moskovits 2005).

Such problems have been addressed in different manners. The selection of the laser wavelength can be crucial in increasing the intensity of the signal by provoking a resonant Raman effect—when the incident energy is close to an electronic transition of the studied molecule—or in diminishing the fluorescence, as laser frequencies in the infrared region are less likely to cause such phenomena. Laser-induced damages can be avoided by carefully controlling the laser power and acquisition time or, in some cases, by coupling a helium beam to the spectrometer. Spectrum processing using mathematical reconstruction algorithms is also useful for eliminating the fluorescence and revealing the hidden Raman bands. Another option, which is being increasingly explored, is the acquisition of the Raman spectrum in the anti-Stokes region, but this has not yet been extensively applied.

Perhaps the most common alternative is the use of surface-enhanced Raman spectroscopy (SERS), which takes advantage of the huge amplification of the Raman signal that occurs when the analyte is in close contact with silver or gold nanoparticles of a particular size and shape (Fleishmann, Hendra, and McQuillan 1974; Aroca 2006). A second benefit of SERS is a drastic decrease of the fluorescence, leading to the acquisition of high-quality spectra. The preparation of SERS substrates is a vast field of research. Nevertheless, the need for direct contact between the nanoparticles and the studied object makes the application of SERS challenging in the field of cultural heritage. Some alternatives are

the inclusion of the nanoparticles on detachable gels, or the preparation of nanoparticle-coated optical fibers in order to produce tip-enhanced Raman scattering (TERS).

Applications

Since the late 1990s, Raman spectroscopy has emerged as one of the most important and effective techniques for the identification of pigments and dyes in heritage objects, due to its high specificity, small amount of sample—when needed—and its feasibility for nondestructive in-situ analysis. Significant efforts have been devoted to the conformation of spectral databases that include minerals, pigments, and natural and synthetic dyes. Most of these databases are available online and are of vital assistance in the identification of materials via Raman spectroscopy.

The technique has been successfully employed in a wide range of studies, including medieval pigments, panel and easel paintings (ancient and modern), dyed textiles, Egyptian papyri, Punic decoration materials, Iraqi stuccoes, and mural paintings from Pompeii. In the Mesoamerican area, Raman has been especially useful in the material characterization of dyes and pigments, including pre-Hispanic mural paintings and codices, and in mineral characterization, mainly of green stone artifacts.

In the field of archaeology, Raman spectroscopy is particularly suitable for the identification of minerals present on walls and stuccoes, for the characterization of lapidary objects, the identification of pigments, dyes, and other constituents of mural paintings, manuscripts, textiles, ceramics, and the determination of corrosion phases in metallic objects (Edwards and Chalmers 2005). Another application is the mapping of small areas. The laser—or object—can be scanned over the object surface, and the intensity of a Raman band of a given molecule can be translated into a color scale and plotted in a 2D graphic, generating an image that contains information on the distribution of such molecules in the analyzed area. Depending on the size of the studied area and the spatial resolution of the analysis, Raman mapping can be time-consuming.

SEE ALSO: Characterization of Pigments; Chemical Mapping; Chemistry in Archaeology; Databases in Archaeology; Dyes; Fibers; Gas Chromatography–Mass Spectrometry (GC-MS); Gemstones; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Instrumental Analysis of Lithics; Nanotechnology and Nanoscience in Conservation; Nondestructive Compositional Analysis of Ceramics; Paper Analysis; Pigment Alteration; Pigments and Binders; PIXE and Material Analysis; Portable X-Ray Fluorescence Spectrometry (pXRF); Raman Spectroscopy; Raman Spectroscopy in Conservation; Vibrational Spectroscopies; XRD and Materials Analysis

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FURTHER READINGS

SEM-EDS and Material Analysis

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Electron microscopy (see ELECTRON MICROSCOPY IN CONSERVATION) in different instrumental configurations has become one of the most versatile characterization tools in the investigation of archaeological materials. Within this frame, scanning electron microscopy (SEM) is universally employed to identify the nature of materials and provide chemical compositions. Indeed, in SEM instruments the coupling of imaging, thanks to the detection of backscattered or secondary electrons, and chemical analysis, thanks to the detection of excited secondary X-rays, represent a powerful tool for the investigation of virtually any kind of material. This entry presents case studies related to ancient glass (see GLASS AND FAIENCE) samples.

Authenticity of archaeological glass

Applying SEM with with energy dispersive X-ray spectroscopy (SEM-EDX) to the study of archaeological glass, we have to keep in mind that it has a history of more than 3,500 years. Nevertheless, the technology of glass production has not changed so much: By heating a mixture of sand (SiO_2), natron (Na_2CO_3), and lime (CaCO_3), a stiff liquid was obtained, which was wound around a core of clay and dung and then reheated in order to smooth the surface. Core-forming remained the dominant technique for producing glasses until the second or first century BCE, when it was found out that a molten blob of glass can

easily be formed in various shapes by blowing short puffs of air into it—thus glassblowing was discovered. From then on, glass became more widely used, as it could be offered for a reasonable price (Frank 1982; Davison and Newton 1989).

According to Zachariasen (1932), pure silica glass has an amorphous (noncrystalline) structure and can be described as a three-dimensional network of $[\text{SiO}_4]$ -tetrahedra. Besides the network former silica (SiO_2), so-called network modifiers (alkali and alkaline earth elements such as Na, K, Ca, and Mg) are added—mostly in the form of their oxides or carbonates—to the batch of raw materials in order to reduce its melting temperature. These compounds break up the silicate network and form terminal $-\text{Si}-\text{O}-\text{M}$ ($\text{M} = \text{Na}^+, \text{K}^+$) or bridging $-\text{Si}-\text{O}-\text{M}-\text{O}-\text{Si}$ groups ($\text{M} = \text{Ca}^{2+}, \text{Mg}^{2+}$). The formation of these so-called nonbridging oxygen sites widens the silica network. The nature and concentration of these network modifiers play a decisive role in the stability and durability of the glasses. Further ingredients, such as colorants, decolorants, and fining agents are present only in minor amounts in the glass (see GLASS COLOR).

SEM-EDX studies could be performed on fragments of ancient glass excavated since the 1950s at Hanghaus I, a Roman insula in Ephesus, Turkey, which was originally built in late Hellenistic times as a luxurious peristyle house, and served, following some earthquakes, from the third century CE as a more simple accommodation unit. Among numerous other findings, more than 1,000 glass objects and glass fragments (Figure 1) were excavated dating from the late Hellenistic to the late Ancient period (i.e., between the middle of the second century BCE and the seventh century CE). A representative cross-section of 106 samples taken from these objects was subjected to chemical analysis. The main objective was the chemical characterization of these glasses, which were archaeologically preclassified into 19 groups (“form-groups” (FG)) based on their typological characteristics such as design, usage, and decoration (Czurda 2007).

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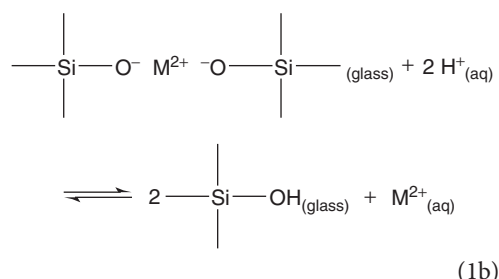
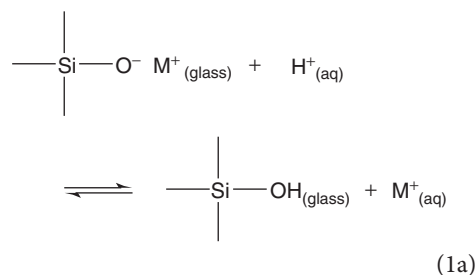
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As all fragments showed more or less thick weathering crusts on their surfaces due to burial for many centuries (Figure 1), small splinters were cut off using a low-speed diamond saw, embedded in resin, and polished with SiC paper perpendicular to their surfaces, enabling the investigation of the unaffected bulk material. The results described in detail in the literature showed 12 major and minor constituents (oxides of Na, Mg, Al, P, S, Si, K, Ca, Ti, Mn, Fe, and Cl) and eight trace elements (oxides of Cr, Co, Ni, Cu, Zn, As, Pb, and Sr). All glasses are of the soda-lime-silica type with SiO₂ concentrations between 64.6 and 77.8 wt%, Na₂O from 10.5 to 18.7 percent, and CaO ranging from 4.6 to 11.3 percent. The contents of K₂O and MgO are below 1 percent for nearly all samples, those of P₂O₅ and SO₃ in most cases below the detection limit, with maximum values also around 1 percent. These low levels of MgO and K₂O argue for the use of soda (a mixture of NaHCO₃, Na₂CO₃, and some other Na-salts) as a flux, typical for glass produced in the Hellenistic and Roman periods.

For reasons of data reduction and to eventually observe cluster patterns in the sample population, factor analysis (FA) for a better interpretation of the results was applied to the original compositional data of Na₂O, MgO, Al₂O₃, Cl, K₂O, and CaO. Scatter plots of the first two factors (representing more than 60% of the original variation in the dataset) help to decide whether the archaeologically defined form groups eventually coincide with the compositional clusters. The loading plot (Figure 2, right) indicates that factor no. 1 mainly contains contributions of Al₂O₃, K₂O, and CaO (positive correlation) and Cl (negative correlation), whereas factor no. 2 “consists” primarily of Na₂O and MgO, both showing a positive correlation. Indeed, the FA score plot (Figure 2, left) exhibits strong clustering: for some form groups (e.g., nos 1, 7, 15, and 19) a single “chemical cluster” (i.e., based on the factor scores of the corresponding samples and hence on the chemical composition) is obtained, whereas some other FGs (e.g., nos 8, 14, 16, and 17) seem to consist of a number of subgroups. The combined archaeological, typological, and statistical results allow for classification of the objects into so-called glass groups (GG), now also exhibiting similar chemical compositions.

Degradation of historic glass

As relicts of the past, archaeological objects are rarely found in their original state—their condition has been altered depending on the nature of the material used and the environment. The exposure of glass to moist air or soil leads to the formation of a so-called leached layer on the surface, resulting in an iridescent appearance, as can be seen in Figure 1, left image. The main reason is an ion exchange mechanism occurring in neutral and acidic media involving the mono- and bivalent network modifier ions (e.g., Na⁺, K⁺, Ca²⁺, or Mg²⁺) in the glass and certain hydrogen-bearing species such as H⁺ or H₃O⁺ or even molecular water of the attacking medium (Equations 1a and 1b). Consequently, the glass surface is depleted in alkali and alkaline earth, while the silicate network remains essentially unaltered. The thickness of this hydrogen-rich layer depends on the conditions: the nature and concentration of the attacking soil, the glass composition and its initial surface structure and morphology, and various other conditions such as the temperature or exposure time.



Similar effects can be observed on medieval stained-glass windows exposed to the ambient atmosphere, as a thin water layer resulting from air moisture, fog, or even rain may be adsorbed on the glass surface, allowing the ion exchange mechanism described above (Figure 3). During

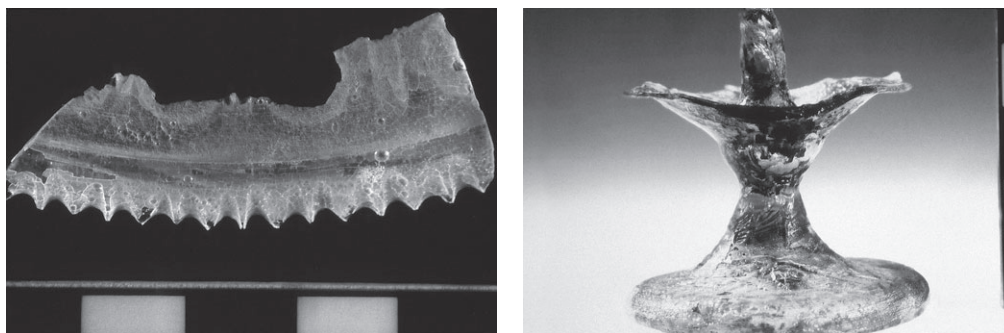


Figure 1 Glass fragments excavated at Hanghaus I in Ephesus, Turkey. Left: Shell with hanging lip and inlaid decor; right: cup foot with button.

the Romanesque and Gothic periods wood ashes (mainly consisting of K_2CO_3) were added to the sand in contrast to the glasses manufactured in the ancient Mediterranean region, where soda present e.g. in the ash of sea-plants or taken from the Wadi el Natron (Egypt) was used as a flux. Its unfortunate consequence is the poor durability of the potash-lime-silica glass, which causes many of these medieval stained glass objects to perish.

Additionally, atmospheric pollutants such as the acidifying gases CO_2 , SO_2 , NO_2 , and O_3 or airborne particulate matter may dissolve in the thin water film, causing an increase in the H^+ concentration and hence accelerating the ion diffusion. As soon as the temperature increases, the water film may evaporate, leading to the precipitation of crystalline weathering products on the glass surface. The chemical composition of

these weathering products is mainly determined by the glass composition and the atmospheric gases. On the surfaces of potash-lime-silica glass with medieval composition, mainly syngenite ($K_2SO_4 \cdot CaSO_4 \cdot H_2O$), gypsum ($CaSO_4 \cdot 2H_2O$), and arcanite (K_2SO_4) can be identified by X-ray diffraction as well as SEM-EDX as dominant weathering products, as depicted in Figure 4. The morphology of the formed weathering products varies from plate-like shape to needles and lanceolate crystals. Furthermore, chlorides of Na and K, Si-containing compounds, weathering products containing K, Ca, and C (possibly carbonates, oxalates, or other organic compounds), and various depositions, often rich in Al and Fe, can be identified. As mainly K-containing weathering products can be detected, a preferential leaching of this element compared to the other

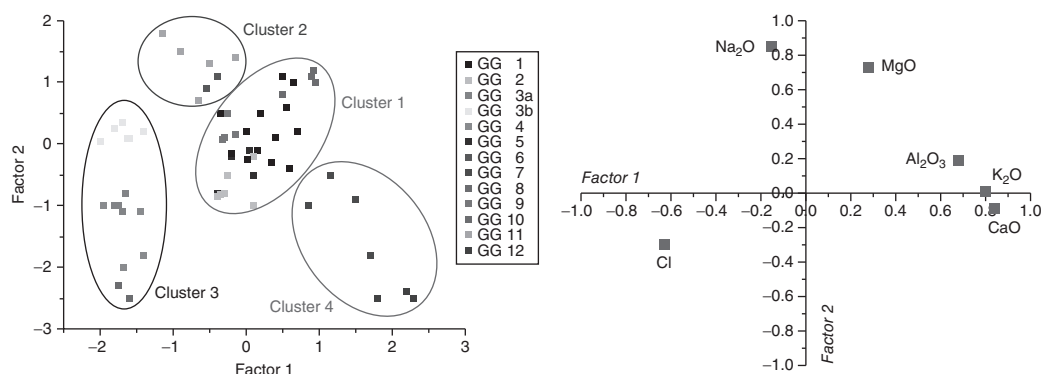


Figure 2 Score (left) and loading (right) plots of the factor analysis results: Factor 1 is determined by concentrations of Al_2O_3 , K_2O , CaO , and Cl , whereas factor 2 contains mainly contributions of Na_2O and MgO .

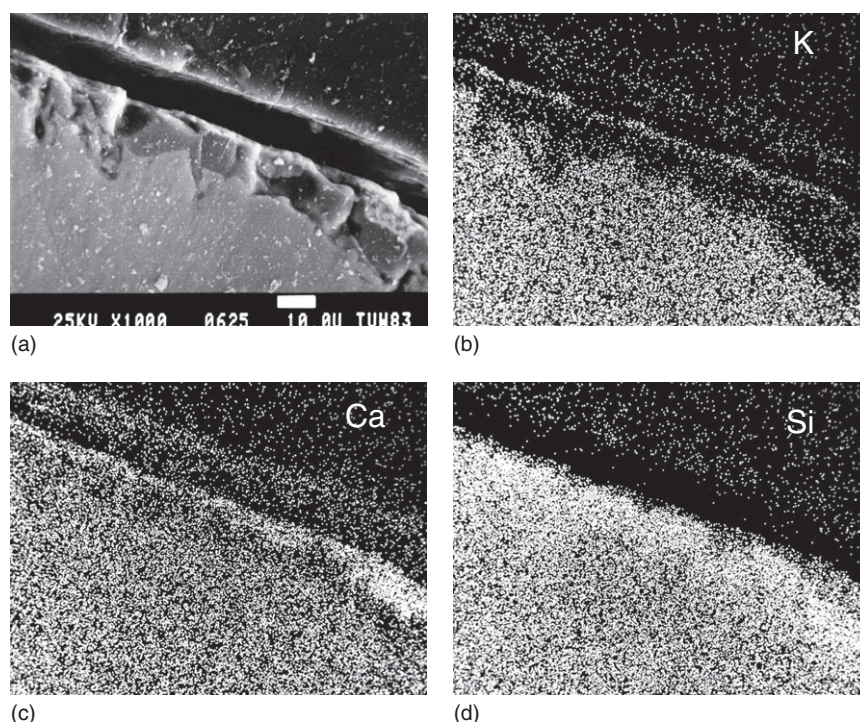


Figure 3 SEM micrograph of the cross-section of a naturally weathered medieval glass (a) with corresponding elemental mappings of K (b), Ca (c), and Si (d).

network modifier ions in the glass (Ca, Na, and Mg) may be assumed.

Analytical investigations have become an important part in the interdisciplinary cooperation of our heritage, if the specific technique can be applied in a nondestructive or even noninvasive way to an archaeological object. Among the large variety of methods available in materials science, as demonstrated in the previous examples, SEM-EDX can be useful for the purposes of assigning, for example, archaeological glass to a specific place or studying the degradation process of archaeological glass buried for even two millennia, as well as of medieval stained glass exposed to the ambient atmosphere for centuries. In this context, modern (multivariate) statistical methods often prove to be useful to achieve additional insights into the data obtained and can support an archaeologist dealing, for example with dating of objects.

Additionally, the results obtained from such studies are indispensable for the development

of conservation and preservation strategies. At the moment, there are several conservation treatments proposed and in practice for preserving our heritage in the field of glass, especially for outdoor objects exposed to the ambient atmosphere: protective coatings with polymers, especially silicon-organic compounds, coating with inorganic materials by applying the sol-gel glassy process or sputtering an inorganic layer on the glass surfaces, and protective outdoor glazing. Additionally, such treatments should provide increased chemical resistance of the glass substrate and sufficient stability against light while preserving the transparency of the object at the same time.

For museums' objects, monitoring of several environmental parameters—such as the relative humidity in the ambient atmosphere, the concentrations of acidifying gases SO_2 , NO_2 , and O_3 , and particulate matter—is of high importance. Glass sensors were developed as dew point sensors with the aim of better understanding the environmental influence on glass surfaces. Such

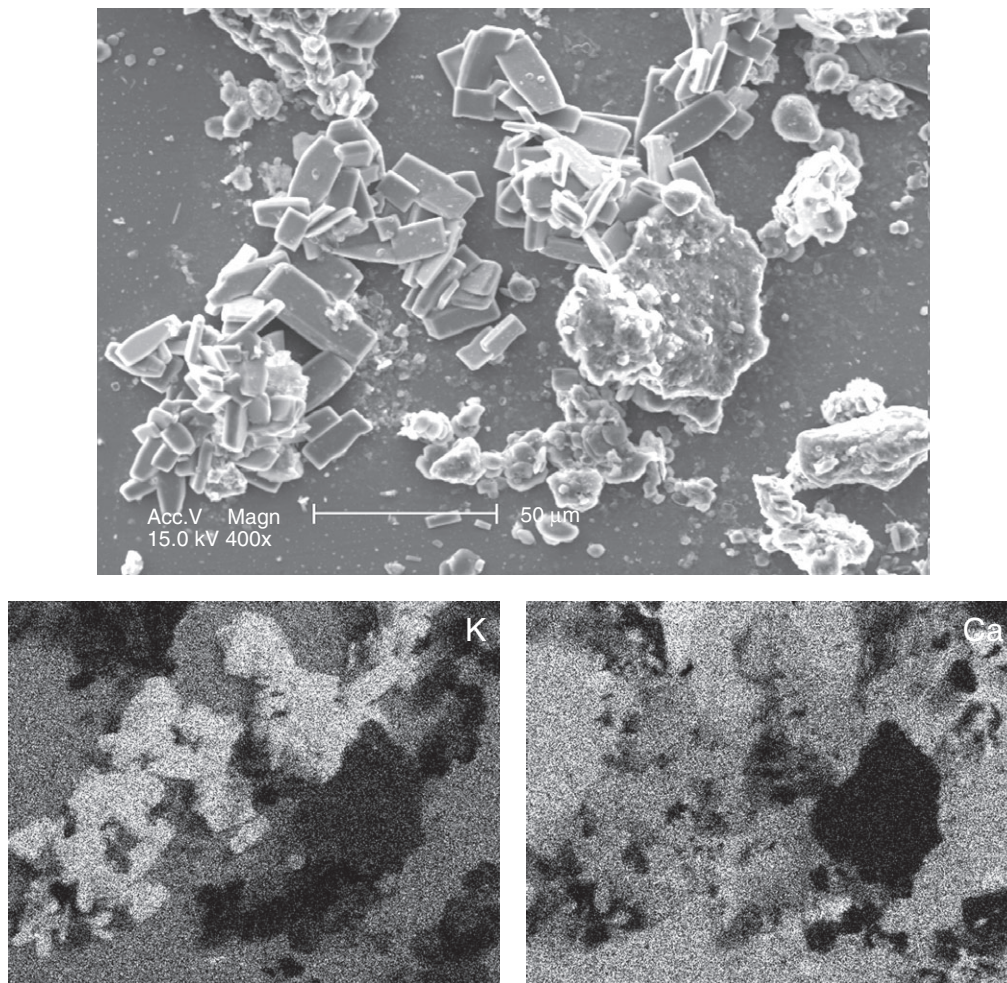


Figure 4 SE image of a weathered surface of potash-lime-silica glass (top) and corresponding X-ray mappings of the elements K (row 2 left), Ca (row 2 right), S (row 3 left), and Al (row 3 right), indicating formation of syngenite ($\text{K}_2\text{SO}_4 \cdot \text{CaSO}_4 \cdot \text{H}_2\text{O}$) and deposition of an Al-rich atmospheric particle.

sensors allow for the detection of condensation on the glass surface, which might accelerate the glass weathering process. Using such sensors, it could also be shown that protective glazing systems for stained glass reduce the danger of condensation on the internal sides of the windows and the total time of the presence of high values of relative humidity in air in contact with the protected window.

SEE ALSO: X-Ray Fluorescence Spectrometry (XRF)

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Soil Chemistry in Archaeology

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Archaeologists look for and examine artifacts to interpret the activities of ancient peoples. However, most material goods and implements used anciently were made of perishable organic substances that did not survive into the artifact record. Perishable organic implements and food may have initially accounted for as much as 90% of an ancient household's artifact inventory (Dahlin et al. 2007). Organic substances eventually decompose to gaseous and soluble substances and are lost to the atmosphere or are leached out of the soil by percolating water, but phosphorus (P) and many trace nutrients—including iron (Fe), copper (Cu), manganese (Mn), and zinc (Zn)—are adsorbed onto soil particles or are precipitated as insoluble compounds and remain for centuries at the location of ancient use. These and other chemical residues of human activities serve as invisible indicators. Many human activities leave behind chemical residues of those activities. By understanding the chemical markers of specific human activities, we can better understand ancient societies through the study of soil organic matter, trace elements, and other nutrients and metals. The architectural, artifactual, and soil chemical data obtained from ancient activity areas provide a robust record of ancient lives.

There are both differences and similarities between the natural soils and the anthropogenic floor surfaces found at areas of ancient human activities. In many parts of western North America, Mexico, and Central America, the major soil parent materials are calcareous sediments and weathered limestone. Stucco and plaster floor

surfaces were often derived from burnt limestone (Barba 2007). During centuries of abandonment the processes of weathering of lime stuccos and plasters yield calcareous soils. Both the soils and the weathered floor surfaces tend to be highly calcareous, with neutral to alkaline pH. The high pH and prevalent calcium and magnesium ions of the soils and floors render anthropogenic P and metal ions insoluble. Stucco and plaster floors were made of burnt lime and limestone gravels that are normally much lower in P, Fe, Cu and other metals of interest than are natural soils (King 2008). The clays and organic matter of soils contain a reservoir of fixed and adsorbed nutrients, therefore natural soils are poor control samples for the estimation of background concentrations of anthropogenic elements. A better estimation of background levels of elements in floors is provided by the levels in samples lowest in concentrations of respective elements (King 2008; Dahlin et al. 2007; Fernandez et al. 2002; Terry et al. 2004).

Soil sediments and anthropogenic floors can bury and provide protection for pollen, phytoliths, bones, architectural components, and nonperishable artifacts over sequential occupations, but the complex chemical and physical processes of soils allow for the accumulation and storage of the chemical residues of those occupations. There are a variety of soil characteristics and chemical analyses that can be used to examine the chemical signature of those activity areas. The roles of specific soil processes in preserving chemical residues of ancient activities are discussed below.

Inorganic soil components

Soils consist of varying proportions of sand, silt, and clay, as well as soil organic matter or humus. The greater portion of fine silts and clays determines the relative surface area of the soil particles. Surface area is important for water retention

and adsorption of organic and inorganic chemical residues.

Ion exchange is the interchange between an ion in solution and on a charged surface. Cations are exchanged on the surfaces of clay minerals and organic matter. The large specific surface area, broken edges, and imperfections in crystal formation within the highly variable soil environment can impart negative charge to the clays. The positively charged cations of the soil solution are attracted to the negative charges on clays and humus. The maximum adsorption of readily exchangeable cations on soil surfaces is termed the cation exchange capacity (CEC). The sum of the cation exchange sites on surfaces is expressed as centimols (cmol) of positive charge per kg. When an ion is replaced on the soil surface, it must be replaced by an equivalent amount of charge to meet the electroneutrality requirement. Whenever an ion is displaced from an exchange site, there is a charge imbalance on the surface of the exchanger, and another ion from the soil solution will immediately exchange place. For example, if a calcium (Ca^{2+}) ion is displaced, it must either be replaced by an ion with a 2+ charge such as magnesium (Mg^{2+}), or two ions with a 1+ charge such as ammonium (NH_4^+).

Soil organic matter

Soil organic matter (SOM) has large adsorptive surface area and high cation exchange, and plays an important role in soil chemistry. SOM consists of many diverse types of organic molecules that react with each other and with the mineral fraction of the soil, making it a complex substance to study. Soil organic matter includes well decomposed humus as well as partially decayed organic tissues from plant and animal detritus.

SOM has several archaeologically important effects on soil chemistry, including chelation, cation exchange, and interactions with organic chemicals. Because of the high specific surface area and local surface charges, SOM has an extremely high CEC. SOM also interacts with organic chemicals and affects their bioactivity, persistence, and biodegradability.

Sorption

Sorption consists of both absorption, the process by which a substance is taken up by and incorporated into a bulk volume, and adsorption, the process by which a substance accumulates at the interface of a solid surface. Adsorption is one of the most important phenomena that occur in soil as it affects the quantity and availability of plant nutrients, metals, and other organic chemicals in the soil. Chemical and physical forces both play important roles in the adsorption of solutes to a mineral surface.

Anthropogenic substances that are retained in the soil

Phosphorus

Soils and floors of ancient human habitations are often elevated in phosphorus concentrations. As hunters, gatherers, and farmers harvested foodstuffs from outside the habitation zone and brought them in to support the nutritional needs of humans, carbon, nitrogen, phosphorus, sulfur, cations and other essential elements were brought into food preparation, consumption, and waste disposal areas. In climates that are cold or relatively dry, many of these nutrients remain in the soil and can be examined as signatures of ancient human activities. In warm and humid climates, most of the carbon, nitrogen, and sulfur have been subjected to microbial decay and have either volatilized to the atmosphere or have been leached out of the soil along with some of the soluble cations by percolating water. Phosphorus and several of the trace elements have low solubility and tend to remain in the soil at the locus of use for centuries. Zones with elevated P concentrations were most likely associated with food preparation consumption and waste disposal activities. Linear patterns of high P in open plaza soils and floors have also been interpreted as zones of vegetable and fruit marketing (Dahlin et al. 2007), feasting activities (Wells 2004), and food storage. Areas of low P concentration have been interpreted as pathways and sleeping areas (Fernández et al. 2002; Terry et al. 2004).

Trace elements

Some of the trace elements in soils at low concentrations are micronutrients that are necessary for plants and animals to live. In high concentrations, however, they are often toxic to living creatures. The micronutrients include Fe, Cu, Mn, and Zn. Heavy metals are those heavier than Fe and include cadmium (Cd), chromium (Cr), cobalt (Co), mercury (Hg), nickel (Ni), and lead (Pb). Ancient people often sought out rocks and minerals for the manufacture of lithic tools, paints and pigments. Some of the micronutrients were used for red pigments, including the iron oxide ochers, mercuric sulfide of cinnabar and vermillion. Manganese oxides form black pigments. Elevated concentrations of these elements in activity areas can give us a further insight into what different areas may have been used for.

Total or extractable element analysis?

Total elemental analysis of P and trace elements can be obtained by X-ray fluorescence (XRF), or by digestion of the sample in strong acids with element analysis by inductively coupled plasma atomic emission spectrometry (ICP-AES). Use of the hand-held, portable “pXRF” works well for many of the heavy elements that emit strong X-rays, but high error rates and interferences have been reported with the measurement of lighter elements (Coronel et al. 2014). Total digestion of samples with strong acids for ICP-AES analysis is both costly and hazardous. Not only do the elements of anthropogenic origin appear in total analysis, but the elements contained in the soil parent materials and ancient humus are also measured. In many cases the small anthropogenic deposition is masked by much larger levels of some elements that were native to the soil or floor materials.

Element extraction procedures have been developed by agronomists and environmental scientists to measure portions of essential nutrients that relate to plant uptake and plant health. Trace element extractions are important in tracking the levels of heavy metals in environmental samples that may be toxic or detrimental to human health. While there are no specific

methods for the sole determination of anthropogenic depositions of elements, the various nutrient availability and toxic element extraction procedures have proven useful in archaeological samples.

Chelates are complex organic molecules that surround and hold metallic ions in solution that would otherwise quickly precipitate. The diethylenetriaminepentaacetic acid (DTPA) chelate extraction method (Lindsay and Norvell 1978) can be used to solubilize surface-adsorbed and slightly soluble trace metals that may be plant available. This method is often used in determining heavy metal contamination of environmental samples, and it is useful in characterizing the metal ions associated with human activities such as food use and mineral use in workshop activities. Dilute acid is also used as an extractant for P, Fe, and heavy metals that are related to ancient activities. Wells (2004) used 1 M HCl extraction of plaza floor samples to study ancient uses at the site of El Coyote in Honduras. Parnell and colleagues (Parnell, Terry, and Golden 2001) compared the results of Classic Maya household floor samples prepared by total digestion (nitric and perchloric acids) with the results of the same samples extracted with Mehlich II for P and DTPA chelate for metals. They reported that the signatures of extractable P and heavy metals were more closely related to cultural deposits than were the total element analyses. They argue that the extraction procedures produced superior results for the interpretation of ancient human activities at Piedras Negras, Guatemala.

Stable carbon isotopes

Carbon, including the heavier isotope of carbon (^{13}C), becomes incorporated and preserved within the soil organic matter or humus as plants decay. Humus molecules are recalcitrant and resist further decomposition to gaseous or soluble compounds. Plant photosynthesis pathways tend to discriminate against the heavier ^{13}C , and therefore plant tissues are depleted in ^{13}C in comparison with the natural abundance of ^{13}C in atmospheric CO_2 . Most plants, including the trees and vines of the forest,

possess a C3 photosynthetic system that is highly discriminatory toward ^{13}C . A few of the tropical grasses (maize, *Zea mays* and sugarcane, *Saccharum* sp.) and certain other plants (e.g., amaranths) possess a more efficient C4 photosynthetic system that is less discriminatory towards the heavier C isotope. For this reason, C4 plant tissues tend to be enriched in ^{13}C compared with the tissues of C3 plants. As the plants die and decompose, portions of both carbon isotopes are incorporated into the recalcitrant humus molecules. Thus, the SOM contains a vegetative history of C3 and C4 vegetation over several centuries. Measurement of the $\delta^{13}\text{C}$ enrichment of the SOM in soils that have lengthy histories of C3 forest vegetation interrupted by periods of clearing for C4 maize agriculture has been used to delineate areas of ancient maize production in the Caribbean islands and in Mesoamerica (Webb, Schwarcz, and Healy 2004; Wright, Terry, and Eberl 2009).

Biomarkers

Biomarkers are described as unique organic molecules produced by specific organisms. These biomarkers may become associated with clay surfaces or are absorbed into humus and thus are preserved for later extraction and measurement. Biomarkers of archaeological significance include the following: animal fats in cooking and dairying residues; plant oils and waxes; and coprostanol and lithocholic acid as indicators of human waste and animal manures, respectively. Plant alkaloids serve as biomarkers of specific plants, for instance: caffeine from coffee, cacao, and a variety of teas; theobromine from cacao; and nicotine from tobacco. Some of these biomarkers have been successfully extracted from pots and potsherds.

SEE ALSO: Archaeological Sciences; Archaeometry; Chemical Mapping; Chemistry in Archaeology; Portable X-Ray Fluorescence Spectrometry (pXRF); Soil Phosphate Chemistry

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Synchrotron-Based X-Ray Analytical Techniques and Materials Analysis

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Synchrotron radiation is the electromagnetic radiation (photons) emitted tangentially to the path of charged particles—generally electrons, or, more rarely, positrons—accelerated at relativistic energies. The phenomenon was postulated in 1944 by V. Veksler in Russia while independently the future Nobel prize laureate E. M. McMillan constructed the first table-top synchrotron one year later. The synchrotron radiation emission was initially regarded as an undesirable energy loss that has to be compensated at cyclotron-based particle colliders. Synchrotrons are nowadays used as intense and versatile sources of photons for the study of matter. At synchrotron facilities, a pulsed particle beam is accelerated at high energy and stored in a “storage ring.” To produce photons, transverse acceleration of the particle beam is achieved through the application of high magnetic fields generated from permanent magnets or electromagnets along the storage ring. Two main categories of magnetic devices are used: bending magnets (magnetic dipoles) and insertion devices in straight sections, consisting of wigglers (succession of dipoles of inverted polarities) and undulators (wigglers with shorter period that lead to coherent summing up of emitted photon beam amplitudes, providing an extreme brightness to the emitted beam). Since the third generation of synchrotrons, their magnetic lattice is optimized to implement undulators. There are about 60 synchrotrons in operation, of which roughly half are third-generation facilities. The photon beams are operated at beamlines. Each beamline is successively composed of an optics hutch, an experimental hutch, and a control cabin. Large-scale synchrotron facilities

operate several dozens of beamlines in parallel, in distinct analytical modalities. Each synchrotron facility runs in a very extended energy range, conveniently described as a critical energy around which the usable energy domain extends. Apart from a few high-energy and low-energy machines, most recent sources operate in a consensus medium range of 2.5–3.0 GeV, which allows the operation of beamlines from the infrared to the hard X-ray range. Modern sources operate in a top-up mode, where the storage ring is refilled in electrons at a low frequency to maintain within typically 1 percent the fluctuations in intensity of the photon beams produced. The specific characteristics of the photon beams generated, in particular their polychromaticity, high flux, low divergence, and small source size, make them particularly suited for an extended range of spectroscopic (see SPECTROSCOPY) and imaging (see IMAGING) techniques of material characterization, particularly in the X-ray energy domain (Bertrand, Cotte et al. 2012). The tunability of the photon beam energy results from the capability to select a narrow energy band-pass in the white polychromatic photon spectrum generated by the photon source, by using crystal or multilayer monochromators ahead of the experimental endstation. Alternatively, a larger energy band-pass may be used in Fourier transform spectroscopy at some beamlines operating in the infrared or UV range. The extreme brightness of the beams, up to 10 billion greater than that obtained with conventional X-ray sources, makes them highly suited to high signal to noise, raster scanning imaging, and/or fast kinetic analyses. Micro- and nano-beams can be generated through focusing optics (Kirkpatrick-Baez mirrors, compound refractive lenses, capillaries, or Fresnel zone plate).

History

The first application of synchrotron methods to archaeology occurred in 1989, when a

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comparison was reported between the content of Gaulish coins in heavy metals and copper, as established from synchrotron X-ray fluorescence (XRF), and neutron activation analyses. Chemical speciation of archaeological systems using X-ray absorption spectroscopy (XAS) appeared shortly later. In 1995, a team of researchers studied the influence of iron and manganese oxidation states on the color of glasses mimicking mediaeval glasses from northern Europe. They studied the L₃ absorption edges of these transition metals, concluding that there was a strong impact of the ferric ion on the glass color. Two years later, new important steps took place with the first use of synchrotron X-ray diffraction (XRD) and of an X-ray microbeam to characterize archaeological samples. In 1997 a microbeam of a few square micrometers was developed using a purpose-built Bragg-Fresnel multilayer lens; the purpose was to study isolated microinclusions from archaeological iron ingots. Since those first interdisciplinary attempts, a steady growth of the use of synchrotron techniques has been observed for advanced archaeometric investigations. The whole sector of ancient materials has published more than a thousand articles that made use of synchrotron techniques thus far.

Elemental analysis

Synchrotron XRF is a powerful method to identify, colocalize, and estimate concentrations in chemical elements. Energies used for multi-elemental studies are typically in the 17–20 keV range. In such conditions, the information depth may not exceed a few hundreds of micrometers in most materials. Archaeological samples are therefore usually studied in a reflection geometry. In current XRF setups, the detection is usually made with a silicon diode detector oriented at 90° to the incident beam in order to minimize scattering from the sample. Synchrotron XRF can be used for point analyses, in 2D maps, or more exceptionally in 3D (e.g., in confocal imaging). By comparison to XRF analysis, which makes use of laboratory sources (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), the synchrotron source provides the tunability needed for an optimal selection of the beam energy

and a very high flux useful for the detection of traces. Energy selection allows to selectively excite and/or avoid specific emission lines so as to further improve signal to noise. Synchrotron XRF allows for the trace detection of transition metals, typically at the ppm level in inorganic matrices and in the 10–100 ppb range in organic matrices. Quantification is facilitated by the use of a monochromatic excitation beam; however, it still requires a good a priori knowledge of the local composition of the “matrix,” that is, of the composition of the sample excluding the analyte, which is rarely the case for archaeological materials. Two-dimensional XRF mapping data are therefore exploited with caution, as variations in the signal originate from fluctuations both in the matrix composition and in the analyte concentration. Synchrotron XRF has been used to study the chemical composition of bulk “homogenous” archaeological material (glass, obsidians, precious metals, gems), surface layers, or stratigraphic buildups in cross-sections (metals, paints, ceramics, associated corrosion products, bones and hair cross-sections, otoliths, speleothems, and wood studied in dendrochemistry). Systems that allow the fast raster scanning of entire sample or artifact surfaces, sometimes designated as macro-XRF scanning (MA-XRF), were recently developed.

Speciation and molecular analysis

High-resolution tunability of the incident X-ray energy allows for excitation spectroscopy and imaging methods that are still unattainable with laboratory sources. XAS informs on the chemical environment(s) of a selected element (see X-RAY ABSORPTION SPECTROSCOPY (XAS, EXAFS, XANES)). The XAS signal originating from distinct compounds in the analyzed spot due to the complex and heterogeneous character of most archaeological samples is averaged. Archaeology mostly use XANES, XAS analysis at energies close to the absorption edge of target elements. Fingerprint XANES signals from samples are compared to standards. XANES was used to establish the speciation of transition metals in glasses and pigments for archaeometry and conservation studies. Sulfur K-edge XANES of lazurite was

shown to provide insights into the provenance of lapis lazuli. The formation of lustered ceramics has been studied in several XANES speciation studies. The role of sulfur and iron in the degradation of waterlogged wood from important shipwrecks, such as those of the *Mary Rose* and of the *Vasa*, has also been studied through XANES. Taphonomic impacts were studied on geochemical paleoproxies (e.g., otoliths). A recent development of XAS that is particularly appropriate for heterogeneous archaeological samples is full-field imaging, where a large sample area is simultaneously characterized using an area detector. Full-field XANES allowed the collection of high-resolution images on entire thin sections of Roman sigillata shards. At very low energies, XANES (in this context often called STXM, scanning transmission X-ray microscopy) and X-ray Raman spectroscopy are promising solutions to speciate low-Z elements encountered in archaeology, such as carbonaceous compounds. In the low-energy range, synchrotron FT-IR has been used to characterize archaeological organic compounds. Compared to its laboratory counterpart, synchrotron FT-IR allows greater signal-noise point and raster-scanning experiments owing to the brightness of the beam. Several classes of organic compounds have been studied, in particular organic binders in ancient murals, archaeological hairs, and textiles, waterproofing resins coating archaeological amphorae, ancient poisons, and consolidation products used in conservation treatments. Synchrotron FT-IR has also been used to estimate the level of remineralization in ancient bones. Recently, UV-visible photoluminescence imaging has appeared as a versatile and sensitive probe of organic traces and crystal defects. A fossil metallurgical state was observed in a highly corroded copper-based archaeological artifact, where contrast originates solely from distinct crystal defects in cuprous oxide.

Structural and textural analysis

Synchrotron XRD has mainly been used in archaeology to identify crystalline phases in mixtures (see XRD AND MATERIALS ANALYSIS). The solid sample is illuminated with an X-ray beam in a transmission (if thin enough) or a

reflection geometry. Occasionally, subsamples are powdered and studied in capillaries. The powder diffraction rings are often recorded with a 2D detector and then azimuthally integrated to create a radial profile of the scattering intensity versus the scattering angle 2θ . Each phase gives rise to a series of rings that appear as sharp peaks in the radial profile. This fingerprint is matched with databases to identify the phase. The low divergence of the synchrotron beam allows attaining a high angular resolution that is needed to resolve overlaps between diffraction peaks, especially for samples containing multiple phases. Synchrotron XRD has been used to study pigments from ceramic shards and mural paintings, corrosion products, ancient cosmetics, and paleoenvironmental proxies. Archaeological materials are often “bad” powders that do not offer completely random orientation of crystallites, which makes structural and textural studies complex. The Rietveld analysis is sometimes used to evaluate the relative amounts in distinct phases within a mixture, while the pair-distribution function (PDF) analysis has been occasionally reported to study ill-crystallized samples without long-range order. Small-angle X-ray scattering (SAXS) has been used to investigate the organization and alteration state in samples with mesoscale organization (e.g., fibers or biominerals).

Morphological analysis

Synchrotron microcomputed tomography (μ CT) allows for the virtual 3D reconstruction of a volume from radiographs collected at multiple angles. Unlike in laboratory setups (see X-RAY RADIOGRAPHY AND COMPUTED TOMOGRAPHY), the low divergence of the synchrotron beam, which can be considered as parallel, allows for an exact reconstruction. Typical current scintillator technology, optics, and detectors allow the formation of megapixel images with a micrometer spatial resolution. In conventional high-energy setups, optimal spatial resolutions will be around $0.3\text{ }\mu\text{m}$, while several beamlines allow for nanotomography (currently with voxel sizes of ca. 20 nm), yet on micrometric samples. Measurements are performed with a “white” or “pink” beam (with a large energy band-pass defined

by carefully selected incoming beam filters and scintillator), or with a monochromatic beam. In the latter case, beam hardening, which leads to significant artifacts with laboratory sources, is suppressed. The small synchrotron source size generates phase-contrast effects that enhance the contrast at the boundary of low-contrasting domains (phase-contrast μ CT). Synchrotron μ CT has been used in few archaeology systems, for instance to decipher texts on highly degraded ancient scrolls, to follow the application of consolidation treatments, or to discriminate wood, antler, or paleobotanic remains according to 3D morphological features. A significant development of synchrotron μ CT is expected in archaeology, as has been observed in paleontology.

More generally, novel developments in spectral imaging intimately couple spectroscopic with morphological characterization.

Future directions

Synchrotron instruments and methods are constantly evolving to integrate novel practical and conceptual developments. Some of the major current evolutions regard the expansion of nanoprobe, the development of ultrafast experiments, and the exploitation of the coherence of the synchrotron beam. Future evolutions that are specific to archaeology were reviewed by Bertrand, Cotte et al. (2012), Bertrand, Robinet et al. (2012), and Bertrand et al. (2016). As archaeological materials are often heterogeneous in composition, structure, and morphology, the ongoing surge of spectral imaging modalities is well adapted to comprehensive material characterization. Spectral imaging will likely contribute to a deeper understanding of the variability of material composition and properties. The development of multiscale imaging modalities allows the study of samples or artifacts at their successive length scales, from high-resolution features (mineral grain size or below) to macroscopic levels. Such “high spatial dynamics” may bring a more robust interpretation, which integrates material behavior over larger sample areas. In addition, innovative ways to exploit the coherence of the synchrotron beam lead to many novel imaging methods (e.g., holotomography, ptychography,

coherent diffraction imaging). Although algorithmically complex, these methods provide accurate structural information and discrimination of phases, even with low-contrasting optical indices, at high spatial resolutions. An adverse effect of the high flux used in analysis (greater intensities, smaller footprint of the beams) is the possible occurrence of radiation damage. Practical assessments, instrumental innovation, and theoretical studies are jointly being carried out to monitor and mitigate side effects of irradiation toward better sample integrity and confirmed validity of the analyses performed.

SEE ALSO: Chemical Mapping; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Infrared Reflectance Spectroscopy; Multispectral and Hyperspectral Imaging of Artworks; Optical Spectroscopies; X-Ray Radiography and Material Analysis; X-Ray Tomography

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TEM and Archaeological Materials

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Transmission electron microscopy (TEM) (see TRANSMISSION ELECTRON MICROSCOPY) and related spectroscopy techniques are widely used in materials science, solid-state physics, and biology to investigate morphological, analytical, and structural features of material specimens down to subnanometric spatial resolution. An important obstacle to the use of this otherwise extremely powerful characterization tool may be either the availability of observable electron transparent specimens or the possibility of preparing them successfully. In fact, it is not always possible to achieve electron transparency, possibly starting from a bulk sample, but still retaining the general representative features of the material to be examined. Inorganic materials require thickness below 100 nm; larger thicknesses, up to 1 μm , are generally acceptable in the case of organic and biological materials, exhibiting intrinsically lower absorption coefficients for their lower average atomic numbers. High-quality samples are definitely recommended to obtain satisfactory and reliable results, and are really interesting for relevant materials study. As a counterpart, it is important to highlight that a very limited amount of material is required for TEM investigations and this is to be regarded as a potential benefit in applying this technique to archaeological research. The scarce availability of material samples and the requirement for a moderately invasive approach can both be tackled with a TEM-based approach.

Although not so extensively, TEM has been profitably used for the characterization of several archaeological finds. However, since many archaeological materials are very heterogeneous in nature, the representativeness of the microsamples used in TEM analyses must be validated by other techniques.

This is, for instance, the case with ceramic finds, whose central role in archaeology is universally acknowledged, despite their ubiquitous presence in materials cultures (see CHARACTERIZATION OF CERAMICS). Ceramics usually display a comparatively fine-grained fired-clay matrix, in which different temper grains, on some occasions millimetric in size, are dispersed. A thorough TEM study is capable of providing data concerning different aspects of the ceramic industry, raw materials, and technological aspects. A systematic and in a way paradigmatic investigation on ceramics can be found in Mata, Peacor, and Gallart-Martí (2002), one of the first archaeometric reports on the possibilities of TEM in archaeological ceramic research. Several aspects and features of ancient ceramics and relevant production technologies are effectively examined. Heat alterations and relevant crystallographic transformations of clay materials were examined, concerning their effects on the resulting microstructure. Selected area electron diffraction (SAED) patterns confirmed the partial thermally induced dehydroxylation of the clay minerals. Crystallographic phases pertaining to different clay poly-types, such as smectite, (dehydrated) illite, and muscovite, were identified, mostly on the basis of interlayer spacings. In addition to the residual grains of altered clays, newly formed structures were detected, like pyroxenes. Not all of them were visible in the X-ray diffraction (XRD) patterns acquired on the same materials. This is a valuable aspect of electron diffraction in TEM: to reveal phases with a total volume well below the detectability limits of XRD (i.e., 2–3 vol.%) but which can still be identified from their morphology during TEM observations and fully characterized by local crystallographic analyses.

Amorphous regions featuring SAED patterns with the typical diffuse halo were observed, with subnanometric “bloated pores.” These pores are formed by the trapping in the liquid phase, a precursor of the glassy structure, of gaseous decomposition products, for example, carbon dioxide released by calcite on decomposing into calcium oxide. All these crystallographic features

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and specific microstructural details, such as the shape and extension of the shrinkage cracks that form as a result of the release of structural hydroxyl groups, and the texture and location of the phases forming during the firing, are important indicators of the pyrotechnological parameters, including the interval of the firing temperature, the duration of the process, the heating and cooling rates, and the firing atmosphere. In a way, the thorough materials characterization that can be achieved thanks to TEM observations and analyses renders very effective and reliable indeed the usage of the detected phases as “mineralogical thermometers.” From a comparison with equilibrium phase diagrams, “calibrated” with the microstructural and chemical data, a realistic interval for the firing temperatures can indeed be estimated. Very helpful for reliable phase identification is the possibility of measuring the chemical composition of the different regions with a spatial resolution comparable to that of the images. This can be effectively accomplished by energy dispersive X-ray spectroscopy (EDXS). The high spatial resolution of TEM observations and associated spectroscopy analyses afford the possibility of investigating even thin surface layers on ceramics artifacts, like enamels and glazes (Mirguet, Roucau, and Sciau 2009). TEM analyses can provide essential clues for understanding the particular chromatic and aesthetic effects of these surface coatings applied to ceramic artifacts.

Thanks to electron microscopy and XRD analyses, the main features of the glazed surfaces (see NANOARCHAEOLOGY) of fragments from a faience (see GLASS AND FAIENCE) vessel excavated in the site of Deir Alla, Jordan were identified (Groot et al. 2006). The glittering and shiny aspect of the glaze was ascribed to chromite (FeCr_2O_4)-based minerals. Submicrometric grains of chromite acted as heterogeneous nucleation sites for nice spherulitic decorative grains. The identification of chromite in these specimens and the relevant archaeological context, dated to the Late Bronze Age of the Near East, allows pre-dating by more than 1,200 years the first certified use of this mineral in the ceramic industry, which was previously attested only in more recent Roman times.

Metals, namely Cu, Au, Ag, Fe, and Co, may act as chromophoric elements also in bulk glasses and have been indeed used for glass coloring (see GLASS COLOR) since protohistoric times (Angelini

et al. 2004). Metals can be found in the glassy matrix as nanometric clusters. The chromatic effect results from the interplay of the composition and size of these clusters. A remarkable example is provided by the notorious Lycurgus Cup in the British Museum. This is a Late Roman glass vessel, decorated with an openwork showing scenes of the death of Lycurgus, the King of the Edoni. The decoration is carved in the glass body and connected to it by shanks and bridges. Perhaps the most famous aspect of this object is its dichroism. It appears opaque green under reflected light, whereas it turns translucent red when illuminated in transmission. The effect is due to the presence of nanometric metallic particles in the 50- to 100-nm range and it is made of an Ag–Au alloy (68:32 approximate ratio) containing 10 percent copper (Barber and Freestone 1990). These results were obtained from an analytical electron microscopy investigation that revealed also the presence of nanometric NaCl crystal, attributed to the reaction with the outer atmosphere of chlorine residues present in the glass. Interestingly, this result has a diagnostic relevance for the storing and preservation conditions. The presence of nanometric metallic particles induces the iridescent effects displayed by pieces of luster pottery, whose color changes according to the incident angle of the impinging light on their decorated surface (Colomban 2009).

Other intriguing structures have been observed in samples extracted from Damascus ancient blades. These blades feature impressive mechanical properties and very sharp cutting edges, resulting from the peculiar thermo-mechanical treatments employed in their manufacture. These weapons, made of high carbon steel, are characterized by a high surface concentration of cementite (Fe_3C) bands, nicely exploited to obtain magnificent decorative surface patterns. It has been proposed that the blades were forged at high temperatures directly from small steel ingots. The raw materials for this alloy were particular ores from Indian mines, whose progressive supply reduction corresponded with the fading of the relevant bladesmith practice. Other essential ingredients of the blades are wood and leaves from specific vegetal materials: *Cassia auriculata* and *Calotropis gigantea*, respectively, employed as carbon carriers. The interplay among these exotic components and the heavy plastic

deformation associated with forging resulted in the formation of nanostructures: for example, cementite nanowires and carbon nanotubes (CNTs) (Reibold et al. 2006). These structures, in particular CNTs, are nowadays attracting an enormous research interest, for several applications and advanced materials, like polymer matrix composites, reinforced and functionalized with CNTs.

TEM studies have been conducted on ancient pigments based on iron oxides. Several aspects have been investigated and the detailed analyses afforded by this technique have provided unique results, extremely important to understanding materials and decoration techniques employed in ancient times. Analyses carried out on the most famous rock paintings in the Lascaux caves have shown that raw materials were prepared and most likely applied to the vault of the cave using bone tools, particularly reindeer antler (Chadefaux et al. 2008). Bone fragments have been identified also in hematite (Fe_2O_3)-based red pigments coming from a completely different archaeological context: the Epigravettian site of Riparo Dalmeri, a rock-shelter inhabited over a time interval beginning 13,400 BP until 12,900 BP. Still referring to this same site, TEM investigations have demonstrated clearly that some of the red pigments used to decorate calcareous stones with animal and human figures were actually of artificial origin (Gialanella et al. 2011). Indeed, hematite-based red pigments can be obtained by heating up goethite (FeOOH) lumps at moderate temperatures (300°C or so) to induce transformation into hematite through the release of molecules of structural water. The occurrence of the transformation is clearly marked by the evident color change from yellow to red. The high spatial resolution that can be achieved with TEM observations and related spectroscopy tools, like EDXS and specifically electron energy loss spectroscopy (EELS), has been strategic to characterizing the surface darkening and, in general, color alteration (see PIGMENT ALTERATION) induced by the interactions of pigments used in oil painting with pollutants contained in the exposure atmosphere (Casadio et al. 2011). Although these investigations are not strictly related to archaeological studies, but rather to the wider frameworks of heritage studies and art history, still they illustrate how TEM observations

are important tools in the study of art materials, and also for diagnostics and restoration purposes (see ELECTRON MICROSCOPY IN CONSERVATION).

SEE ALSO: Characterization of Pigments; Electron Backscatter Diffraction (EBSD); Optical Microscopy; X-Ray Fluorescence Spectrometry (XRF)

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Textiles

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Introduction

Textiles represent one of the earliest human craft technologies and applied arts, and they have been a fundamental part of subsistence, economy, and exchange (Barber 1991). As such, textiles can tell us about social, chronological, and cultural aspects of past societies, and at the same time give us a unique opportunity to come very close to the individual people in their capacity as both users and makers of textiles. Strictly speaking, a textile is something woven, as the word textile is derived from Latin *texere* (to weave). However, the term is often applied to any flexible material made of interwoven or intertwined fibers. A textile, is not simply a binary system of spun or twisted fibers, but first and foremost a result of complex interactions between resources, technology, and society (Andresson Strand et al. 2010). Knowledge of textiles is thus key to our understanding of a multitude of human issues, being able to tell us about social, chronological, and cultural aspects of past human societies.

Textile use goes back to at least the Paleolithic and is intimately connected with the use of clothes by humans. Nevertheless, DNA study of the evolutionary split between head and body lice concluded that people first began wearing clothes at least 190,000 years ago. Those early garments were most likely made of animal skins and hides, which continued to be used as cloth throughout history and to this day. The use of simple textiles and strings is documented by the so-called Venus figurines of the Upper Paleolithic (i.e., by 27,000 BP).

The earliest direct evidence comes from the Czech site of Pavlov, where imprints of twined fabrics have been found on clay. During the following millennia, the technology spread across Eurasia and with the arrival of humans to the

Americas, throughout North and South America. By the Neolithic period, there is a veritable explosion of textile craft with a variety of techniques present: Direct evidence comes from the Levantine area, Anatolia, and Europe.

How far we can push back textile history has to a large extent been determined by textile preservation. Like all organic materials, textiles are subject to a much more rapid decomposition in comparison to materials such as ceramics, stone, and metal. Nevertheless, textiles survive much more frequently than is commonly believed, and, although unevenly distributed and very dependent on environmental conditions, the quantity of material is constantly increasing, particularly thanks to improved excavation and conservation procedures. Preservation conditions also affect the analytical procedures that can be applied to a particular find. Dry conditions, presence of salt, waterlogging, and temperatures below 0 °C preserve textiles almost unaltered. In contrast, charring and mineralization in the presence of metals (in particular copper and iron) and calcium substantially alter the physical and chemical structure of the organic material.

Whatever the condition of preservation, textile recovery greatly depends on excavation methodology and conservation procedures. Thus, in archaeology, the micro-excavation approach, in which entire blocks of earth containing archaeological material are lifted and brought to the laboratory, where they are then carefully excavated by conservators using special equipment and under controlled conditions, has been especially successful in textile recovery and preservation. Their prompt consolidation, documentation, and conservation, given the usually advanced state of degradation, are then essential.

Textile analysis

While basic structural analysis constitutes standard operating procedure in textile research, within recent decades, textile investigation has been enriched by many new analytical methods

derived from natural sciences which can be used to gain new kinds of information (Good 2001; Andersson et al. 2010). Scientific analytical methods allow us to ask a variety of questions about many different aspects of textiles, in particular:

- What materials were used to make the object (characterization)?
- How was the object made (technology)?
- When was the object made (dating)?
- Where was the object made (provenance)?

Furthermore, scientific analysis of the artifacts is essential in order to understand the ways textiles deteriorate, and to determine the best practice to preserve, conserve, handle, and protect the objects for the benefit of present and future generations.

Textile characterization

Textile quality and appearance are dependent on the materials of which the textile has been made, that is, fiber and dye. By studying fiber on a microscopic level we can come closer to understanding the types of raw material used which varied geographically and chronologically and are also indicative of textile origins. Fiber analysis can furthermore address issues of selective breeding (sheep) and cultivation (flax, cotton), processing of fibers (wool sorting), and their wear, which are essential to the understanding of agriculture, animal husbandry, domestication, and technology.

Fiber identification

The main fibers used until the advent of synthetic organic materials were derived from plants (cellulose based: linen, cotton, ramie) and animals (protein based: wool, silk). The biological source of fibers may be identified by optical or digital microscopy on well-preserved textiles using modern reference materials for comparison (both longitudinal and cross-sections). However, many cellulose-based fibers (flax, hemp, nettle) have very similar morphological characteristics and their identification requires the

use of a polarized light microscope to identify microfibrillar orientation, hemp being z-oriented and flax and nettle being s-oriented. Degraded fibers from archaeological and historical textiles are often more complicated to identify and require more sophisticated methods. The best-available method for fiber identification is currently scanning electron microscopy (Rast-Eicher 2016). In highly degraded textiles, alternative methods of differentiation have been further developed, using synchrotron radiation microbeam diffraction and microfluorescence (Müller et al. 2006).

The new methods of amino acid composition, DNA, and protein analyses are being developed for protein-based fibers and allow animal species identification and possibly even differentiation between breeds of the same species.

DNA analysis is a rapidly developing research field with great potential in archaeology, and new genetic research aims at decoding ancient fibers in archaeological textiles. DNA analysis was used recently to identify flax and hemp in the ropes from Christmas Cave in the Dead Sea area. Besides allowing identification of species, mitochondrial DNA (mtDNA) has been widely used to explore origins of domestic sheep. This work, however, has been done primarily on material extracted from sheep bones recovered from archaeological contexts. Techniques and methods are getting more refined, allowing extraction of minute amounts of DNA, such as present in hair shafts, which can then be replicated. Ancient DNA can shed light on gene function, for example hair color, and DNA extracted from textiles may permit tackling questions dealing with ancient sheep breeds and sheep domestication, and development of silk and cotton (Brandt et al. 2011).

Another method to identify animals to species is proteomics. Analysis of relict proteins has shown that the Salish of west-coast North America made their blankets out of dog hair, interweaving it with goat, and that the woolly dog was superseded by sheep by the late nineteenth century (Solazzo et al. 2011).

Fiber analysis

Fiber investigation, however, is more than just identification of material source. By studying fiber on a microscopic level we can come closer

to understanding issues of selective breeding/cultivation, selection, and processing of fibers, and their wear. These issues are essential to the understanding of ancient agriculture, animal husbandry, domestication, and technology.

Analyses of wool fiber fineness, for example, are used to determine the fleece type of ancient sheep. Assessment of fiber quality is based on the diameter measurement of 100 fibers per thread and statistical analyses resulting in a distribution diagram. Wool contains three parts, differing in structure and size: kemp, hair, and the wool itself. Michael Ryder established an evolutionary scheme for wool development based on fiber diameter measurements. Ryder demonstrated that, over the course of time, selective breeding has produced increasingly finer and more uniform wool. Ryder's model has been adapted in recent investigations to account for the fact that the fiber in a textile is a product of numerous processes: breeding, selection, processing, and finishing. The method also allows distinguishing between sheep wool and goat fiber. A large database of measurements is needed to start identifying clusters of wool quality types, which in conjunction with DNA and protein analysis may provide data on ancient and historical sheep and other animal breeds.

Dye analysis

Addition of color has been an integral part of textile making and has important consequences in pattern design and meaning (Cardon 2007). The identification of active dye components and their combination is key to understanding dyeing technology, exchange, aesthetics, value, and meaning. Before the advent of synthetic dyes in the nineteenth century, all dyes were natural, made from various plants and animals. Dye identification can be significant for tracing the origins of textiles, particularly in combination with fiber analysis, since dyes were generally produced from locally available species. Thus, certain dyes were extremely precious and traded over long distances. In the cases of faded or discolored textiles, the original colors may be identified through dye analysis.

Currently the best method for dye and mordant analysis is high- and ultra-performance

liquid chromatography (HPLC/UPLC) (Vanden Berghe, Gleba, and Mannering 2009). The technique allows the identification of the chemical dye components, but does not always enable determination of the source or the specific hue of the textile, making the analyst's experience very important. Since the sources for dyestuffs are numerous throughout the world, it is important to take into account the archaeobotanical data from the area where the dyed textile has been found. Analysis of large series of samples will permit identification of clusters which can be correlated with fiber, and isotopic and biomolecular data.

Textile dating

An approximate date can be ascribed to many textiles by virtue of art historical comparisons; however, this will always be a subjective opinion that is based upon the experience of the researcher. Other methods of dating are based on context or comparison of the object to similar items found at dated archaeological sites, yet the results are simply *terminus ante quem* as the textile may have been old when it was buried. Furthermore, the traditions of continuity meant that certain technical or artistic features were reproduced virtually unchanged for centuries; thus, one item seemingly identical to another could have been made hundreds of years later or indeed earlier than the "dated" example.

AMS radiocarbon dating

The most consistent way to accurately date fibers has been by using radiocarbon analysis. It is a radiometric dating method that uses the naturally occurring radioisotope carbon-14 (^{14}C) to estimate the age of carbon-bearing (i.e., organic) materials. The accelerator mass spectrometry (AMS) method, developed since the late 1990s, is proving a particularly important dating tool. Textiles made over 500 years ago are especially suitable for ^{14}C dating and may even give more precise dates than other materials (Mannering et al. 2010). Dating a large number of textiles, particularly of a specific type, such as carpets, can help in tracing chronological developments

in techniques and styles. The technique is also important for identification of fakes.

Amino acid dating

Recently, a new method for dating silk was suggested (Moini, Klauenberg, and Ballard 2011). The technique relies on the tendency of amino acids in protein to flip from what is known as a left-handed form known as “L” amino acids, to a mirror-image right-handed version, referred to as “D.” The shift in the orientation of the molecule happens at a steady rate, making it possible to tell how old a silk thread is by looking at the ratio of D to L amino acids. One of the advantages of this method, particularly important in the case of usually very fine silk objects, is that while techniques such as radiocarbon dating require several milligrams of silk for each test, this method needs just one-hundredth that amount. The method is particularly accurate for objects dating within the last 500 years that have not been affected by a burial environment, that is, historical textiles.

Textile provenance

Identifying provenance of artifacts in absolute terms is often difficult if not impossible. This is especially true of textiles, which, made with widespread and long-lasting techniques and materials, may defy typological classification, may lack visible reference to their origin, and, furthermore, were moved and traded over vast distances. An important aspect to understanding archaeological textiles is identifying where they were made, and thus exploring the movements of raw materials and finished artifacts, for what this can tell us about the social, economic, cultural, and technological links between sites and regions.

Strontium (Sr) isotopes

In archaeology, strontium (Sr) isotopes have been widely applied, mainly for the purpose of reconstructing human and animal migration routes in antiquity. Strontium isotopic signatures are conveyed from eroding geological materials through soils and the food chain into the human and animal skeleton, where Sr substitutes for

calcium (Ca). Since the path of the strontium isotope ratio through the food chain is unfractionated, it is possible to apply the method also to animals and plants and hence to their products, in this case fiber and consequently textiles. Strontium isotope ratios have been shown to be a unique indicator for wool fiber provenance in Denmark (Frei et al. 2009). This newly developed methodology using thermal ionization mass spectrometry can either be used independently or as a control for typological and/or technical analysis, although it should be applied with caution in some cases as recent studies indicate that $^{87}\text{Sr}/^{86}\text{Sr}$ ratios of archaeological wool textiles recovered from wet burial environments do not accurately reflect wool provenance even after cleaning (von Holstein et al. 2016).

The results of isotopic tracing analysis must be compared with the local geological environment in order to ascertain if the textile was made of local fiber. Thus, this tracing technique relies on local and regional geological differences of the local rock and soil properties, and precise geological maps are necessary. Ideally, such reconstructions would entail the collection of samples from exposed bedrock, soil, plants, and water, along with small fauna and archaeological human remains from the region. While it is not always possible to delineate precisely the exact geographical provenance, the technique provides a potential method for distinguishing between local and nonlocal origin.

Stable isotopes

Combined carbon, nitrogen, and hydrogen isotopes have only occasionally been used in archaeology to establish geographic origin. They have instead been widely employed to investigate diet. However, there is extensive evidence of these isotopes' geographic variation from analysis of keratin in studies of modern human hair and bird feathers and from food traceability studies.

Gradients in stable isotopes identified in modern studies of European sheep meat and wool have now been successfully applied to medieval archaeological wool samples from Iceland, the United Kingdom, Germany, and Sweden (von Holstein et al. 2016). Analysis has shown that the isotopic composition of wool

and bone collagen samples clustered strongly by settlement, demonstrating the feasibility of provenancing keratin preserved in anoxic water-logged contexts. The same methodology has been applied to silks and could be extended to other animal and vegetable fibers.

Conclusion

Throughout the human past, textile manufacture was practiced at all levels of society and was one of the most labor-intensive of all occupations. As such, it was an industry of great cultural and social importance and should be factored into any balanced assessment of the past. Over the last decades, textile studies have developed into an important new field of archaeological and historical research, largely due to the development of a wide variety of scientific methods that permit their closer characterization, dating, and provenancing. The accumulation of data and the constant improvement and development of analytical techniques are permitting a more synthetic approach to the history of textile art and technology, demonstrating how much we can learn about the culture, society, technology, and economy of the past through textiles.

SEE ALSO: Conservation of Fibrous Materials; DNA: Mitochondrial; DNA: Next Generation Sequencing; Dyes; Fibers; High Performance Liquid Chromatography (HPLC); Mobility and Oxygen Isotopes; Mobility and Strontium Isotopes; Optical Microscopy; Synchrotron-Based X-Ray Analytical Techniques and Materials Analysis

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Volcanic Rock Sourcing

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The issue of volcanic rock sourcing in archaeological research needs to take into account two important factors: the role of lithic raw material in heritage studies and the role of volcanic rocks among different lithic materials.

For the first factor, additional information about the different aspects of past human settlements can be drawn from studies on stone tools. In particular, the latter can highlight the technological and cultural characteristics of a given society, emphasizing its interactions and adaptation to the surrounding environment. The numerous studies on these tools show that the choice of stones was determined not only by the easy access to the source, but also by their features (workability, appearance, color, and so on). For these reasons, the individuation of the exact outcrop or quarry where rocks were sourced by ancient people represents a big challenge. By identifying the provenance of these artifacts, archaeologists can reconstruct the movements of human groups, their management of geographic space, their relations with other neighboring groups, and their access to resources. Moreover, this set of information helps to define the social and economic habits of ancient populations.

The determination of the provenance of archaeological finds is generally possible by comparing their petrographic features (texture and mineral assemblage) and geochemical characteristics (major element and trace element composition) with those of the possible sources of raw material.

In order to compare them, the first step is the collection in the field of samples from the presumed rock source, which has macroscopic features similar to the raw materials of the archaeological finds. The determination of petrographic and geochemical properties of both geological and archaeological samples is the second step.

To identify the geochemical features of the samples, nondestructive analytical techniques are preferred, because they preserve the integrity of the samples. Among these techniques, X-ray fluorescence (XRF) applied in a nondestructive way or portable-XRF (pXRF), proton-induced X-ray emission (PIXE), neutron activation analysis (NAA), and scanning electron microscopy (SEM) are the most effective. In addition, in the past 20 years, laser ablation—inductively coupled—plasma mass spectrometry (LA-ICP-MS), a microdestructive analytical methodology, has also proved to be a powerful tool for in situ determination of trace element patterns in archaeological samples.

As for the second factor mentioned above, among the different types of lithic raw materials employed to produce artifacts, volcanic rocks have always been among the most important and widely used. Volcanic rocks are formed when magma is placed onto the surface of the earth either as coherent lava flows during an effusive eruption or as pyroclastic deposits during an explosive eruption. In relation to the rate of heat loss or cooling, different magmatic fabric can be generated; that is, a magma with a rhyolitic composition can solidify into the following fabrics: phaneritic, aphanitic, glassy vitrophyric, pumiceous, or pyroclastic.

An interesting example of the use of volcanic rocks in sculpture is given by the megalithic Moai statues of Easter Island, Chile (Gioncada et al. 2010). The latter represent the heads and upper bodies of the inhabitants' ancestors which, according to most archaeological interpretations, colonized the island, coming from southeast Polynesia. The stones used to fashion the Moai statues and their topknots are represented by several volcanic rocks characterized by different depositional mechanisms and chemical compositions outcropping across the island. Most of the megalithic statues were made using two types of pyroclastic rocks. Only a few of the Moai were fashioned using lavas of trachytic instead of the tuff. Concerning the pedestals, several types of mafic lavas were used for their building (Gioncada et al. 2010).

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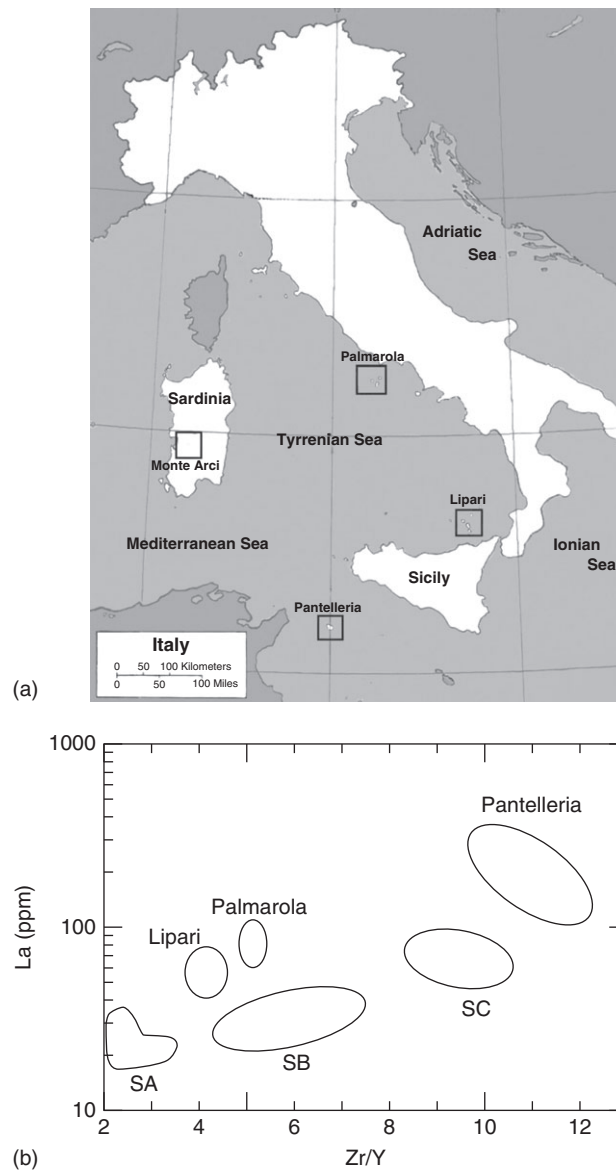


Figure 1 (a) Locations of obsidian outcrops (squares) in the peri-Tyrrhenian area. (b) Zr/Y versus La binary diagram for obsidian outcropping around the Tyrrhenian Sea. Zr, zirconium; Y, yttrium; La, lanthanum.

Source: Barca et al. (2007) and Tykot (2002).

Specifically, obsidian is an aphyric/subaphyric volcanic glass, typically black, but also gray-greenish or red-black at times. It has different degrees of transparency from shiny to semi-opaque. Since ancient times, various populations preferred obsidian, not only to produce artistic artifacts, but also to make tools and weapons for

everyday life, because of its attributes of fracture predictability and exceptional cutting-edge quality.

Numerous studies, focusing on the characterization of obsidian, demonstrate that: (1) it geologically outcrops in a limited number of locations; (2) although obsidian composition is

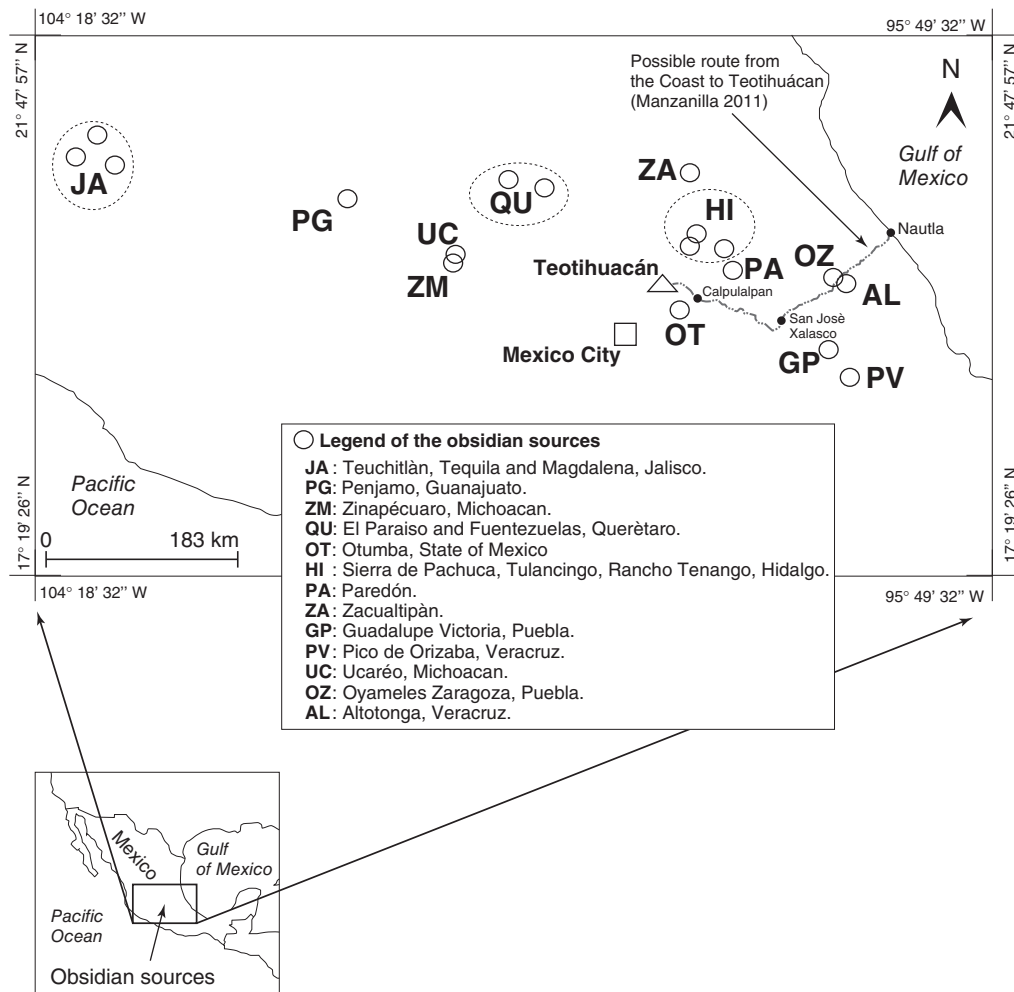


Figure 2 Obsidian outcrops in Mexico.

Source: Reprinted from *Journal of Archaeological Science*, Vol. 40, Barca, D. et al. Provenance of glass shards in archaeological lime plasters by LA-ICP-MS: Implications on the ancient routes from the Gulf of Mexico to Teotihuacan in Central Mexico, pp. 3999–4008. Copyright (2013), with permission from Elsevier.

extremely felsic (usually with 70% or more of SiO_2), the different sources are typically differentiated on the basis of chemical compositions: for example, oxide percentages of other major elements (Al_2O_3 , Na_2O , K_2O , and CaO), and the trace and rare earth (RE) elements content. These peculiarities explain why the chemical characterization of archaeological obsidian is typically used for provenance studies.

Two examples are herewith reported, referring to the peri-Tyrrhenian and Mexican areas. Experimental researches indicate that sources

of obsidian in the peri-Tyrrhenian area are only found in a limited number of places: on the islands of Lipari, Pantelleria, Palmarola, and Sardinia (Acquafredda et al. 1999; Barca, De Francesco, and Crisci 2007; De Francesco, Crisci, and Bocci 2008; Tykot 2002) (Figure 1a). From a geochemical point of view, trace and RE element concentrations of these geological sources demonstrate that six or seven compositional groups can be distinguished. In general, many properties, such as alkalinity and the nature of crystallites content, permit the discrimination

of these six or seven groups. However, the concentrations of trace and RE elements are the most effective discriminant factors. The sources of Lipari and Palmarola show an extremely homogeneous trace elements composition within the group and they are easily distinguishable from the others. On the contrary, the Pantelleria obsidian shows great variability within the group, but trace element concentrations are typically different. The obsidians of Monte Arci complex in Sardinia are then subdivided into three or four groups named SA and SB, sometimes subdivided into SB1, SB2, and SC. They show similar trace element compositions, but their differences are relevant enough to separate them (Figure 1b).

The case studies conducted on ancient artifacts from various settlements located in the peri-Thyrrhenian area demonstrate that a comparison of archaeological and geological chemical compositions allows us to assign the provenance of obsidian used for Neolithic artifacts to a definite source.

A different situation can be depicted in Central Mexico, where many obsidian sources have been recovered. In detail, they outcrop in the states of Mexico, Hidalgo, Tlaxcala, and Puebla (Carballo, Carballo, and Neff 2007; Cobean et al. 1991) (Figure 2). Despite the high number of sources outcropping in this area, their geochemical characterization (Cobean et al. 1991) shows that they can be discriminated using the trace and RE element concentrations.

The case study on the provenance of obsidian material recovered in Teotihuacan is very interesting. Teotihuacan was one of the most important cities in ancient Mesoamerica during the Classic Period (200–600 CE). It had the economic and political control of hundreds of communities over a large geographical region. The importance of Teotihuacan was also based on the exploitation of obsidian from two nearby sources—Otumba and Sierra de Pachuca (also known as Sierra de las Navajas)—located respectively 10 and 50 km away from the city (Carballo et al. 2007; Gazzola et al. 2010). In addition, many artifacts were produced and exchanged with the elites of foreign regions to extend the political control over remote territories. Indeed, some obsidian finds show different provenance, that is, Paredón (Puebla) and Zacualtipán (Hidalgo).

Recent studies have shown that in addition to obsidian, Mexican people appreciated other types of volcanic material. Indeed, the Teotihuacans used a pyroclastic deposit made of glass shards of rhyolitic composition as an aggregate in the manufacture of plasters (Barca et al. 2013). The glass shards provenance study turned out to be particularly complex. First, to determine the chemical characteristics of the glass shards spread within plasters, two micro-analytical techniques were used: SEM-EDS to determine the major element composition and LA-ICP-MS to determine the trace element composition including RE elements (Barca et al. 2013).

The comparison between geological and archaeological data, once again, has proved to be decisive. Although two main sources of obsidian, Otumba and Sierra de Pachuca, are located near Teotihuacan, comparison of the results obtained on the glass shards within the plasters with the database of Mexican obsidian (Cobean et al. 1991; Carballo et al. 2007) allowed the identification of the magmatic system of Altotonga, Veracruz as a possible source. These data confirm that a vast amount of foreign raw materials and products arrived in Teotihuacan during the Classic Period, as recently suggested also by Carballo et al. (2007), who pointed out that Teotihuacan had a more complex procurement system for the lithic materials than previously thought.

The results obtained show that people living in the compound of Teopancazco near Ciudadela took shards from a source located 180 km from Teotihuacan. This distance had to be walked, since, in ancient Mesoamerica, neither draft animals nor wheels, and thus no chariot, existed.

An integrated analysis of the evidence from Teopancazco excavations indicates that there was an important link between Teopancazco and the Gulf Coast of Mexico (Manzanilla 2011).

However, the reasons for the use of glass shards as an aggregate material are still unknown. Two hypotheses have been advanced. The first is technological: Perhaps the Teotihuacans had guessed that the use of glass shards made the plasters more resistant. The second is that, perhaps for symbolic reasons, the inhabitants of Teopancazco wanted to build their compound with materials coming from the route they had followed from the Gulf Coast to Teotihuacan, tracing their identity to that distant land.

SEE ALSO: Archaeometry; Cements, Mortars, Binders; Chemistry in Archaeology; Chert, Silice, and Obsidian Sourcing; Geoarchaeology; ICP-MS and Material Analysis; INAA and Material Analysis; Mass Spectrometry (MS); Neutron Activation Analysis (NAA); Optical Microscopy; Portable X-Ray Fluorescence Spectrometry (pXRF); Raman Spectroscopy; Tephra and Volcanic Ash Analysis; X-Ray Fluorescence Spectrometry (XRF); XRD and Materials Analysis

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X-Radiography and Ceramics

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Discovered by Wilhelm Röntgen in 1895, X-radiography was quickly put to use to investigate a multitude of human medical conditions. Soon, its potential for art, archaeology, and geology became apparent, and it was utilized to examine ancient human and animal mummies, metals, ceramics, paper, paintings, and soil (Lang and Middleton 2005). The first applications of X-radiography to ceramics date back to the 1930s and 1940s, but its full potential was only realized in the 1970s when Rye published his seminal work on the fundamental patterns and rules underpinning ceramic X-radiography (Rye 1977, 1981). This work was further expanded on by Carr (1990), Carr and Riddick (1990), and Berg (2008). X-radiography has major contributions to make to our understanding of ceramics. However, it is only one of the many tools that are available to researchers, and it is always recommended that as many techniques are used in conjunction with each other as possible.

X-radiography is a type of electromagnetic radiation that penetrates objects in proportion to the atomic density of the materials and thickness of the object, and captures the outgoing radiation as a grayscale image on a monitor or photographic medium. With the proliferation of digital X-radiography in medical and industrial contexts, it is now easier than ever to gain access to suitable facilities. While industrial facilities provide better-quality X-ray images, medical facilities are ubiquitous, may be portable, often offer good value for money, and are adequate for most research purposes. As each machine is different, researchers will need to experiment first to find the best exposure parameters for the given ceramic assemblage.

The advantages of X-radiography for the study of ceramic objects are manifold: Equipment and

facilities are widely available, the technology is nondestructive, it can be used for both fragments and complete objects, it allows speedy acquisition of images, it provides quick image enhancement with commercially available software and relatively fast interpretation of the image, it offers good value for money, and it can be undertaken on individual objects as well as on large assemblages. The only known disadvantage is that ionizing radiation may change a thermoluminescence (TL) date of the object by up to 20 percent. It is important to note that most of the research has been carried out on pottery. However, the investigatory principles can be applied to any clay object, such as figurines, bricks, or even drainage pipes. X-radiography is most commonly utilized to answer the following research questions:

- identification of the object and its condition;
- identification of the material(s) present;
- identification of manufacturing method(s);
- identification of joins, faults, breaks, repairs, and reuse;
- identification of finishing methods and decoration;
- identification of forgeries.

Of these, scholars working with ceramics are mostly concerned with the identification of manufacturing methods and characterization of the fabric.

It was Rye (1977, 1981) who recognized that different primary forming techniques leave characteristic fingerprints in the clay body that can be made visible through X-rays. Pinching, drawing, coil-building, slab-building, molding, and wheel-throwing differ in the alignment and distribution of inclusions, shape and orientation of voids, evenness and thickness of vessel walls, and the visibility of seams where sections of a pot were joined together. Pinching can be recognized by an alignment of inclusions parallel to the surface, but without a recognizable horizontal or vertical orientation. Drawing orients inclusions weakly vertically when viewed in cross-section and voids appear flattened and

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circular when viewed normally. Coiling results in a preferred horizontal orientation of inclusions and elongated, horizontal voids. Inclusions aligned parallel to the surface but without a predominant orientation is a characteristic pattern of slab-building. Molding produces a parallel but random alignment to the surface. Lastly, inclusions aligned parallel to the surface but set at a diagonal orientation when seen from the front are characteristic of wheel-thrown pots (Rye 1981).

Secondary forming techniques, such as scraping, trimming, smoothing, and adding sections, do not normally interfere with the radiographic visibility of the primary techniques (Berg 2008; Carr 1990). The exceptions are the paddle-and-anvil technique because it applies so much pressure that it obliterates all primary features and results in extreme thinning of vessels which removes all extant features. Secondary forming techniques and surface treatments are therefore best understood through macroscopic analysis.

Investigating forming techniques can lead to exciting discoveries, such as the existence of two distinct manufacturing traditions (Attic and Rhodian) for Aegean Bronze Age transport stirrup jars. Used to transport olive oil, the main distinction lay in the forming of the “fake” spout as either a hollow or solid part of the vessel (Leonard et al. 1993). Vandiver (1987), using the no longer supported xeroradiography, was able to reconstruct the slab-building technique used in the Zagros region of modern-day Iran in around 3000 BCE. By using so-called thick sections (whereby a vessel is cut into vertical slices whose cross-sections are then X-rayed), Vandiver was able to reconstruct the precise shape, size, and sequence with which each slab was applied to form a vessel. Nowadays, this kind of analysis can be undertaken using computed tomography (CT). A major study of Cretan Bronze Age pottery by Berg (2009) illustrated the great variety of forming techniques utilized by ancient potters. It also showed that potters often combined multiple forming techniques on the same vessel, such as a Minoan amphora which was constructed by wheel-throwing, coiling, and drawing. The power of this tool is not limited to pottery. Analysis of clay figurines, for example, has proven very effective in understanding step-by-step how they were constructed.

X-radiographs may be helpful in characterizing ceramic fabrics by determining the size, proportion, type, and general mineralogy of inclusions and/or tempering materials. The technique can only do so when the inclusions or temper have different radio-densities from the clay body which makes them stand out. Based on these differences, scholars have been able to distinguish between classes of minerals, though specific attribution is often problematic when inclusions have similar chemical composition, morphology, and radio-densities. In contrast, organic inclusions often burn out during the kiln firing and leave a recognizable void behind (Carr and Komorowski 1991).

Using X-radiography, Blakeley, Brinkmann, and Vitaliano (1989) were able to divide their sherd assemblage of Pompeian Red Ware successfully into two major fabric groups. The validity of these groups was subsequently confirmed using petrology and chemical analysis. Carr (1990, 1993), in contrast, was interested in understanding whether X-radiography could be used to determine whether body sherds found in close proximity to each other during excavation belonged to the same fabric group and hence possibly the same vessel. X-radiography has the ability also to detect unusual tempering practices or combinations of different clays on the same vessel. Despite its great potential, it is always recommended that petrography and chemical analysis are undertaken alongside.

X-radiography can be used to discover structures hidden inside a complete vessel. One of the very earliest applications of this technique discovered that Peruvian water jugs contained an internally hidden whistling mechanism. Repairs—ancient and modern—are often clearly visible macroscopically. However, where there is doubt, X-radiography will be able to detect them easily if they were undertaken with materials of a different atomic density. An example of a known repair is the insertion of a metal pin into the fake spout of a Bronze Age stirrup jar. Damage incurred during the life history of a ceramic object, such as firing cracks, temperature cracks, or stress breakages, will also be clearly visible in an X-ray.

New technologies such as CT have the potential to supersede X-radiography in archaeology in time because they can offer a 2D and 3D view

of the object at macro- and nanoscale, allowing for quantitative and qualitative analysis of temper and pores/voids. However, the disadvantages are currently too great to establish them as a viable alternative. X-radiography is now almost exclusively digital and much improved in quality. Taking X-rays is quick, inexpensive, and nondestructive, and industrial, medical, or veterinary facilities are abundantly available in most locations across the world or can be brought into museums. The resulting images can be viewed immediately and enhanced quickly, if required, using commonly available software packages requiring minimal training. In contrast, CT scanning necessitates for objects to be brought to the facility (portable machines are available, but prohibitively expensive and large), scanning time is measured in minutes and hours rather than seconds, imaging software is highly specialized, thus requiring extensive training, and processing a single image can take hours.

SEE ALSO: Petrography and Ceramics; Raman Spectroscopy; Raman Spectroscopy and Material Analysis; Terahertz Imaging in Conservation; X-Ray Radiography and Material Analysis; X-Ray Radiography; X-Ray Tomography

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X-Ray Radiography and Material Analysis

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X-ray radiography is an established technique used to obtain images by means of X-rays; the first X-ray images were produced by W. C. Röntgen in 1895. Currently, its importance in the analysis of materials is due to the fact that it is considered to be a non-invasive or non-destructive technique, since the radiation passes through the objects without damaging them. The X-rays make it possible to observe the non-visible structure of certain objects, including features of its interior.

In this sense, it is possible to analyze structural weaknesses, internal deterioration, and production defects, as well as to determine superimposed layers of materials such as, for example, surface coverings or pictorial layers. It is also often possible to evaluate through this technique both the mistakes of the producer of the object, as well as traces of his tools and even signatures or inscriptions, thus allowing us to identify the artist or craftsman, or a certain technological tradition, as well as the structure of the object.

Therefore, X-ray images have been used for more than a century for the preliminary or diagnostic analysis of the internal structure and the techniques used in various heritage objects, including those considered as objects of art and those we identify as archaeological. In addition, for the preservation and restoration of the same, the use of radiographic images is an essential tool to examine previous losses, replacements, and restoration methods that would otherwise not be visible.

X-rays are a high-energy electromagnetic radiation that travels like ordinary light, but has the ability to traverse most objects. The X-ray intensity received by the object depends on the thickness of the object and the density and elemental composition of the material or materials with which that object was produced. Thus, if

one exposes an X-ray sensitive film together with an object to an X-ray transmission, an image of the contour and interior of the object is obtained. The denser areas of the object absorb a greater number of X-rays; therefore, those areas where the film is less exposed are clear.

The equipment used throughout the years, from the end of the nineteenth century to the present, for the examination of heritage objects in general, and archaeology in particular, have been primarily those of medical use, both conventional equipment and those machines used for mammography and/or tomography. Equipment manufactured for quality control of industrial products was then successfully tested. However, it is only after the interest that these experiences with heritage objects have awakened in the industry that, in the last third of the twentieth century, there have also been fixed and mobile equipment specially designed to radiograph art and archaeological objects (e.g., Gilardoni et al. 1994) with the aim of studying objects located in exhibitions, or housed in locations such as site museums (Lang and Middleton 1997).

Along with technological advances, X-ray equipment has become increasingly digital in nature. This has resulted in digital radiography, and digital radiography by luminescence. In general, it can be said that the latter type of radiography is based on the luminescent properties of a phosphor plate, which maintains a latent image after being exposed to X-rays, and then is digitized in the reader module using a system based on a laser beam to form the image matrix as a digital file (Gómez López 2015).

The use of the digital version of the radiographs, instead of analog, meant a new set of aims, objectives and advantages, among which stand out:

- the speed of this technique, enabling greater productivity;
- reduction in the number of erroneous exposures;
- longer shelf-life for image plate (IP) boards;
- improvement in image quality;

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- greater ease of interpretation;
- better storage and reproduction of images;
- reduction in use of harmful chemical materials, as well as costs.

In archaeological sciences, the radiographic technique is considered as a useful tool because it is non-invasive, but it must be used with caution, as in the case of ceramic or textile materials, since once they are exposed to X-rays, they are not fit to be dated by thermoluminescent techniques.

The radiographic technique is applied primarily to human remains, to determine some osteopathy or, for example, to interpret the way in which cranial deformations were performed, among other characteristics. It can also be applied to virtually all types of complete or nearly complete objects, of different materials, which for reasons of preservation cannot be analyzed invasively.

This technique is also applied to fragmentary materials in order to evaluate whether they are fragments from the same archaeological piece (Greene and Hartley 2009). Radiographic techniques have been applied for the preliminary analysis of ceramic and metallic materials, especially when the surface cover or corrosion layer does not allow observation of the production technique.

Radiography is also useful in cases of archaeological materials whose shape has been distorted, such as wooden objects or textiles, clothing and related items (O'Connor and Brooks 2007), or when their parts cannot be understood, as in the case of writings, certain sculptures that may be composed of combinations of different materials, such as wood, metal, and ceramics, or when it is a composite object extracted from an excavation, such as a burial urn soon to be micro-excavated in the laboratory.

Thus radiographic techniques are used in archaeology to visualize procedures and sequences of manufacture or industrial production of an object. But they are also used in the diagnostic stages of conservation or restoration of archaeological objects, allowing characterization of repairs carried out on them in a previous and undocumented way, either executed during its original lifetime of use, or in contemporary contexts. In these latter cases, the radiographic technique often reveals restorations made with materials different from the original, whether

compatible or not, and which have been partially or completely obliterated by surface finishes based more on artistic than archaeological considerations, which are also known as "false historical".

In order to apply a radiographic technique it is essential to possess not only contextual information for the heritage object, but also its thickness along its contour or shape and the basic elements that make up its matter, as well as prior knowledge of how the variables used by the X-ray equipment work: voltage (kV), current (mA), exposure time (t), as well as the distance between the focus and the film (dff) which, under different formats and for each case, depends on the object to be irradiated.

In this last regard, despite the indications given by the specific publications on this subject, it is always necessary to make an adjustment in these variables by considering the parameters established by other authors, together with those resulting from a first experimental test with materials of known composition that act as comparative samples (Chaves Castanedo 2015), in order to establish the best exposure parameters, both for the type of equipment used and the type of object to be irradiated, ultimately to achieve an adequate protocol to follow for future examinations. Some examples of such adjustments can be found in López, Caramés and Acevedo (2010), or in Oliveira et al. (2013).

Once the radiographic images were obtained, traditionally they were analyzed simply by the use of a negatoscope, such as those found in medical offices. Internal details of archaeological pieces could be observed, as well as zones of union of parts, or the use of different techniques of manufacturing or industrial production through the marks left by the instruments used in the operational chain.

Thanks to modern equipment, we can now read the results of X-ray irradiation digitally, either because the images have been scanned or because they are directly delivered in this format. In this way, qualitative analysis can be carried out as before, but including techniques such as manipulating the contrast between the different shades of gray that are observed in the images of the irradiated object. Some quantitative observations can also be made, such as adjusted measurements of some of the inner elements to the pieces, or of density of elements

compared with standardized tables according to the materials analyzed.

Finally, although the first tests with radiographic images of different archaeological materials were often done with medical instruments, currently the main institutes of conservation and restoration, as well as laboratories integrated with the largest museums of art and archaeology of the world, or those dedicated specifically to archaeological sciences in some universities, already own their own equipment. There is even equipment specially designed to be transported to the sites of large heritage objects.

SEE ALSO: Archaeometry; Conservation; Experiment in Archaeology; X-Radiography and Ceramics; X-Ray Radiography; X-Ray Tomography

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XRD and Materials Analysis

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X-ray diffraction (XRD) is one of several scientific techniques that are applied to the materials analysis and cultural interpretation of inorganic mineralized artifacts such as ceramics, lithics, ores, plaster, faience, pigments, slag, and metal. It can also be used to study crystalline phases in some colored and opaque glasses, as well as being applied to crystalline organic materials such as bone and teeth. The technique is used to characterize and in some cases quantify the mineral constituents of these types of artifacts, which in turn can provide information about their raw material sources. In the case of synthetic materials such as ceramics, plaster, pigments, metals, and slag, XRD data can also be used to investigate their manufacturing technology, use, and alteration. The approach is usually applied alongside other methods of compositional characterization, such as transmitted and reflected light microscopy (see PETROGRAPHY AND CERAMICS), scanning electron microscopy (SEM), and instrumental geochemistry (see X-RAY FLUORESCENCE SPECTROMETRY (XRF), ICP-MS AND MATERIAL ANALYSIS, NEUTRON ACTIVATION ANALYSIS (NAA)). In most cases a small amount of powder is removed from the artifact; however, small objects such as coins can be analyzed nondestructively, by being placed in the diffractometer. This chapter outlines how XRD can be applied to the materials analysis of archaeological ceramics as well as to the study of several other artifact classes mentioned above. For technical details on the technique, see Pollard et al. (2007, 113–16) and Heinmann (2016).

Ancient ceramics are composed of clay minerals, naturally occurring mineral inclusions, and in some cases also mineralized “temper” material,

which is intentionally added. X-ray diffraction can be used to characterize archaeological ceramics in terms of the minerals present and their relative abundance. In this respect it provides data broadly similar to those of thin-section petrography. However, XRD can also be used to identify the minute clay minerals present in low-fired ceramics and the presence of “neo-phases” formed in high-fired specimens. Ceramics are mineralogically complex when compared to other inorganic artifact types and can contain many different mineral species. This can make diffractograms challenging to interpret owing to the presence of multiple peaks, regular overlaps, and large numbers of possible matches (Figure 1a–b). For this reason it is advisable, when characterizing coarse ceramics, to combine XRD with thin-section petrography, particularly if one attempts to generate quantitative data.

Once collected, mineralogical data can be used to classify different archaeological ceramic specimens by detecting similarities and differences between them. This can be done manually or automatically, via multivariate statistics. However, extreme differences in firing conditions can alter the specific mineral assemblages of sherds that were made from identical raw materials (Figure 1a–b). This means that compositional groupings derived from XRD data may reflect both raw materials and technology.

Mineralogical data collected via XRD can be used to interpret the types of raw materials used in the manufacture of ceramics. The presence of specific minerals may be indicative of the use of a particular type of clay deposit (e.g., glauconite forms in shallow marine clay, illite is characteristic of deep-water marine environments). Mineralized temper such as sand or crushed rock may also be used, though distinguishing between this and intrinsic inclusions already present in coarse clay deposits is not possible using XRD alone.

By comparing the mineralogical composition of sherds with potential clay and temper deposits sampled in the field, it may be possible to identify raw material sources used for ceramic manufacture in the past. If it is assumed that clay was not

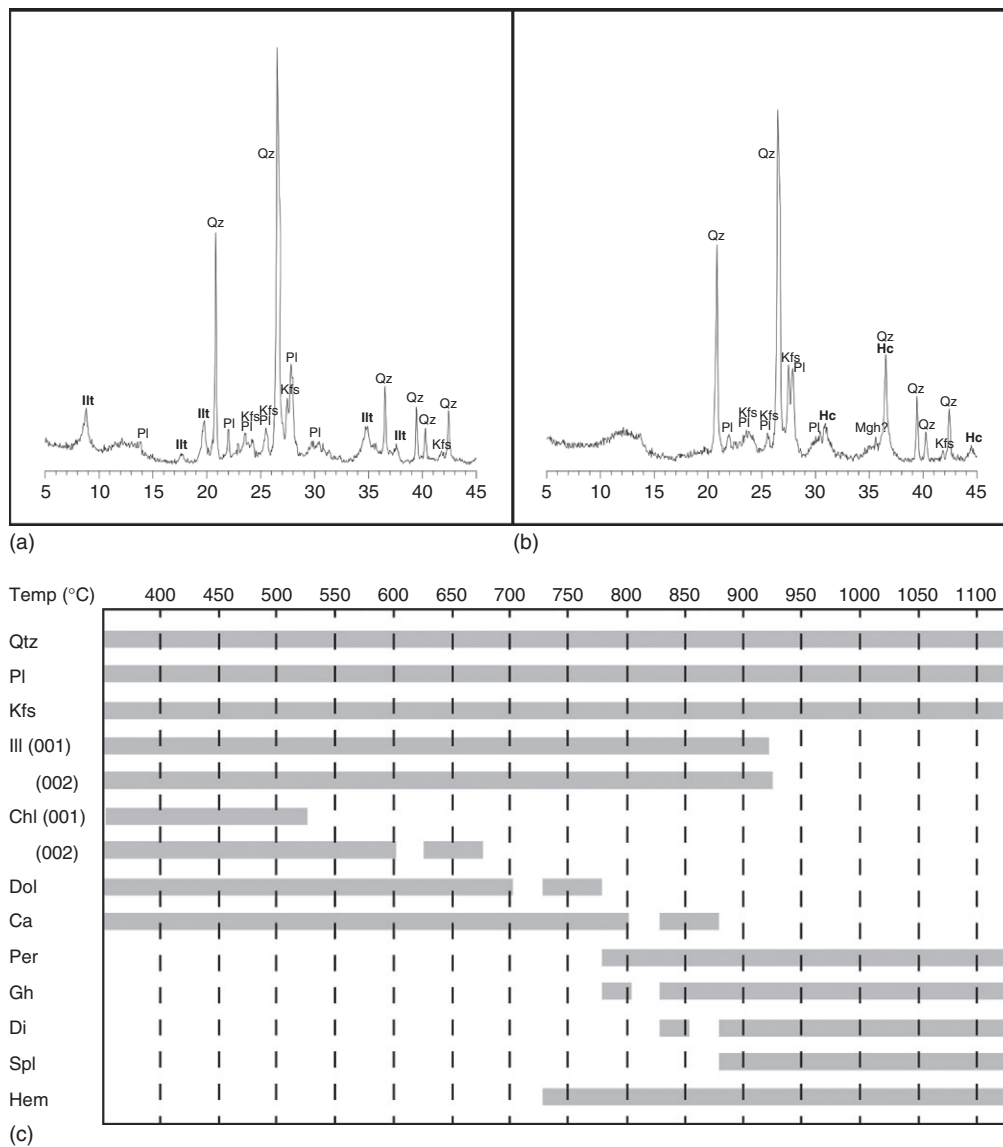


Figure 1 X-ray diffractograms of two pottery sherds that were made with the same raw materials but were fired at different temperatures. a: Sample containing the clay mineral illite that is suggestive of firing below ca. 800 °C. B: Sample without illite, but with significant quantities of hercynite, which forms above ca. 900 °C. C: Bar diagram of stability of minerals during the firing of ceramics. Abbreviations: Qtz = Quartz; Pl = Plagioclase feldspar; Kfs = Potassium feldspar; Ill = Illite; Chl = Chlorite; Dol = Dolomite; Ca = Calcite; Per = Periclase; Gh = Gehlenite; Di = Diopside; Spl = Spinel; Hem = Hematite. b: Republished with permission of Springer from Travé et al. (2014, fig. 9, p. 399). c: Modified from Maritan et al. (2006, figs. 4 and 5, pp. 6–7).

transported over significant distances, then this can be used to determine production location or “provenance.” X-ray diffraction can play a role in this endeavour, either alone or in combination with other compositional approaches. Statistical classification of XRD data from ceramics and potential raw materials may be used to find possible matches.

The main application of XRD to the materials analysis of archaeological ceramics is in the reconstruction of manufacturing technology. This includes various strands, such as the investigation of paste preparation, the identification of the ingredients used in decorative layers such as slips, paints, and glazes, and the reconstruction of ancient firing temperatures or “archaeothermometry.” The latter has been the subject of numerous studies and is therefore well developed. It relies upon the detection of the presence or absence of a number of indicator minerals that are stable at specific temperatures during the firing of ceramics. As firing temperature increases, certain unstable “primary” mineral phases are lost (e.g., calcite, dolomite, illite) and new stable “firing” minerals will form (e.g., gehlenite, hercynite, mullite, wollastonite; see Figure 1a–b).

The sequence of mineral transformations in ceramics has been investigated experimentally and “bar diagrams” have been proposed (Maggetti 1982; Maritan et al. 2006; see Figure 1b). These can be used to interpret the firing temperatures of sherds from XRD data. It is advisable to refire small fragments of samples at various temperatures and to detect when the original level of firing has been exceeded. The specific transformations occurring in ceramics are dependent on the original composition of the raw clay and any temper, so certain mineral species featured on the bar diagrams (e.g., calcite) or their alteration products (e.g., gehlenite) may not be present. The sequence and level at which mineral alteration takes place are different in oxidizing and reducing firing atmospheres, and the “soaking time” at maximum temperature is also important. This means that the relationship between mineralogy and temperature is not straightforward. The incomplete oxidation of sherds during firing can result in the occurrence of different phases in the core and in the margins of a specimen. For these and other reasons, the

relevance of XRD experiments to archaeological pottery has been questioned.

The mineralogical composition of ceramics can be altered once they have been discarded and buried. Postdepositional alteration can affect adversely the characterization of ceramic raw materials, the interpretation of provenance, and the reconstruction of technology. X-ray diffraction can be used to identify “transformation products,” which can then be taken into account when classifying archaeological pottery and establishing kiln reference groups. Soluble minerals such as calcite, dolomite, and gypsum are particularly susceptible to postdepositional alteration via groundwater, and high-temperature neo-phases, including gehlenite and wollastonite, may be unstable after firing. The sintered clay matrix of ceramics can alter to mixed-layer minerals over time, and hematite may convert to pyrite in anoxic environments such as under the sea.

An important related application of XRD within archaeological materials science is the investigation of natural or artificial pigments used for painting and for decorating ceramics and other artifacts. It can be of help in characterizing the mineral colorant(s) that were used, as well as in studying the weathering and degradation of pigments. For example, the complex manufacturing process of Egyptian blue, which is considered to be the first ever synthetic pigment, was deciphered thanks to data from XRD (Pradell et al. 2006; see Figure 2).

X-ray diffraction is used extensively on metallic artifacts to investigate inlaid decorations made of precious and semiprecious stones, enamel, glass, and niello. The technique is essential for distinguishing, for example, between white inlays made of limestone (calcite) and shell (aragonite), or for identifying the different types of bronze tinning (e.g., Meeks 1986) as well as of niello (e.g., La Niece 1983). It can also be used to study the production of intentional patinas created on metal artifacts for aesthetic purposes and to distinguish this from other types of decoration, or from natural surface corrosion formed over time. Natural and artificial patinas have a different crystal-lattice formation and, as a consequence, exhibit distinctive XRD patterns (Craddock 2009). The study of corrosion layers on metals, glass, and glazes is an important field in archaeological science and conservation studies. The

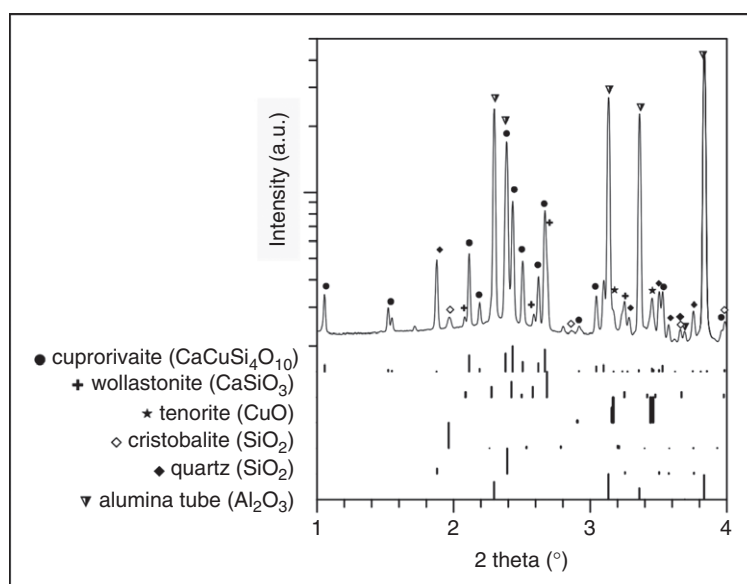


Figure 2 X-ray diffractogram of synthetic Egyptian blue replica produced with high alkali mixture (3% Na_2O) obtained at a temperature of 1000 °C. Republished with permission of John Wiley & Sons from Pradell et al. (2006, fig. 3, p. 1428).

corrosion patinas on artifact surfaces are made of specific secondary products that reflect the environment in which they were buried and may inform conservation strategies. X-ray diffraction data can be read in combination with “Pourbaix diagrams,” which represent the stability of a metal as a function of potential and pH in an aqueous system. By using XRD it is possible to investigate the composition, morphology, and profile of the corrosion products, which are all essential for understanding the corrosion mechanisms and for developing treatments to prevent or slow down such processes. The most common application has been the study of corrosion products on bronzes, iron, and silver artifacts.

The technique of XRD can be used in the study of slags produced as a by-product of metallurgical processes. It should be carried out in combination with optical examination, in order to ascertain whether the identified phases are residual minerals or newly formed crystals and to assess their distribution in the samples, both of which are essential for technological interpretations. It is also possible to investigate via XRD the material sourcing, provenance, quality, and variability as well as the grade of metalliferous ores.

Despite their mainly amorphous composition, certain glasses and glazes can be studied by XRD. These include those with crystalline opacifiers such as antimonate, as well as colorants such as cuprite. In the investigation of glasses, XRD should be applied alongside complementary techniques such as Raman spectroscopy (see RAMAN SPECTROSCOPY) and SEM.

Important methodological developments that have been applied to the study of archaeological materials include micro-XRD (μXRD) (e.g., Berger et al. 2016) and grazing incidence XRD (GIXRD). The ongoing development of portable XRD (pXRD) devices and the use of a synchrotron source to produce X-rays (SR-XRD) are both likely to have a significant impact in the field of ancient materials characterization and conservation owing to their potential for noninvasive analysis. The latter provides high spatial resolution and high beam intensity.

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Analysis of Variance and Covariance

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Variance is the statistical index we use to measure the degree of variation of archaeological magnitudes (length, width, height, weight, volume, perimeter, etc.) or relational index (elongation, shape–form, circularity, concavity, etc.). It should be defined as the expectation of the squared deviation of a random variable from its mean, and it informally measures how far a set of numbers are spread out from their mean. It is calculated by *averaging the squared differences from the mean*:

$$\text{Var}(X) = \frac{1}{n} \sum_{i=1}^n (x_i - \mu)^2$$

where μ represents the mean. However, the variance calculated from the observed archaeological record will in general not match the variance of the original population of artifacts that were produced and used in that place at that moment. Given that the true variance of a population is not known *a priori* and must be computed somehow, we should use an *unbiased sample variance*:

$$s^2 = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})^2$$

The variance of different variables can be compared to obtain information about how magnitudes vary in different populations. There are two ways of comparing variance. *Covariance* is a measure of the joint variability of two variables, for instance, length (X) and width (Y) measured in a population of stone tools. The sample covariance is defined in terms of the sample means, and it is usually calculated as:

$$\text{cov}(X, Y) = \frac{1}{n-1} \sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})$$

For instance, if the stone tools with longer lengths also have greater width, and the same holds for the lesser values, we can say that the covariance between length and width is positive. In the opposite case, when the greater values of one variable mainly correspond to the lesser values of the other (i.e., the variables tend to show opposite behavior), the covariance is negative.

Covariance gives no information about the possible equality of variances. We can test the existence of this circumstance, assuming that when two values are equal, their ratio should be equal to one. In the case of two different populations A and B :

$$H_0 : \frac{s_A^2}{s_B^2} = 1$$

H_0 follows an *F-distribution*—also called Snedecor's distribution—with sample size $(A) - 1$ and sample size $(B) - 1$ degrees of freedom, if the null hypothesis of equality of variances is true. The null hypothesis is rejected if the *F-distribution* value is either too large or too small for the appropriate degrees of freedom.

When comparing the diversity of archaeological material from different assemblages, we are in fact comparing two variables: a magnitude measured for each artifact, or *dependent* variable, and some categories that group the observed artifacts, or the *independent* variable. The dependent variables represent the outcome of human activity in the past, whose variation is being studied. The independent variables represent factors or causes—the potential reasons for variation. For instance, we can analyze the differences in human left femur length in male and female skeletons from an ancient cemetery (Table 1). In this case, the goal is to determine the effects that the biology of sex has on body size.

Alternatively, we can study how ancient huts at different contemporaneous settlements in the same regions show any differences in the degree of curvature of its perimeter (Table 2). The purpose is to determine the effects that the different social or economic functions of each site, or even

Table 1 Measurements of human left femur length (cm) from an ancient cemetery.

Male	Female
48.5	43.5
47.8	42.6
49.32	45.9
50.5	47.6
46.7	40.3

the cultural identity of the inhabitants, had on the shape of its buildings.

Instead of a mere variance comparison, we should compare differences among group means and their associated variation within group and between groups. This is usually called *analysis of variance* (ANOVA). In its simplest form, it provides a statistical test of whether or not the means of several groups are equal, and therefore generalizes the Student's *t*-test to more than two groups. ANOVAs are useful for comparing (testing) three or more means (groups or variables) for statistical significance. It is conceptually similar to multiple two-sample *t*-tests, but is more conservative (results in fewer type I errors) and is therefore suited to a wider range of practical problems.

In a one-way analysis of variance, the observed variation is partitioned into components

attributable to different sources of variation. There are two main sources of variation: *between group* and *within group*. It is the same as asking whether the data values within any one settlement or category are all the same, taking into account that there is always some *within-group* variation. In the same way, there may be some *between-group* variation that may affect the general variation among measured data. If different assemblages had different formation processes, or different sites were the consequence of different human activities, such formation processes may have influenced the magnitude we are studying in different ways. Because of sexual dimorphism, femur lengths are different between men and women. If settlements 1–4 were functionally or culturally different, then the size and shape of their buildings would be different. ANOVA tests the non-specific null hypothesis that all four population means are equal.

The between-groups variance can be considered as the variance of the mean from each group or class. It is estimated by:

$$\text{Between-groups variance} = \frac{\sum_g n_g (\bar{x}_g - \bar{x}_T)^2}{g - 1}$$

where n_g is the size of group g , and the means are the mean of each group and the mean of all observations. The between-groups sum of squares has

Table 2 Curvature of perimeter of ancient huts in settlements in a particular region.

Settlement 1	Settlement 2	Settlement 3	Settlement 4
0.2	0.86	0.2	0.3
0.5	0.81	0.3	0.5
0.8	0.7	0.12	0.6
0.7	0.85	0.2	0.3
0.1	0.9	0.11	0.5
0.4	0.9	0.2	0.4
0.2	0.8	0.2	0.9
0.2		0.3	0.1
0.2		0.2	0.2
0.4		0.19	0.5
0.15		0.3	0.6
0.2			0.8
0.4			0.3
0.4			0.5
0.3			
0.2			

an associated degree of freedom: the number of groups minus one.

The within-groups variance is derived from the total variance, taking into account the number of groups. This is sometimes called the *error* measurement, and it can be estimated from:

$$\text{Within-groups variance} = \frac{\sum_g \sum_i (x_i - \bar{x}_g)^2}{n - g}$$

where the x_i are those in group g . The within-groups sum of squares has an associated degree of freedom: the total number of values minus the number of groups.

Finally, the test statistic F is computed as:

$$F = \frac{\text{Between-groups variance}}{\text{Within-groups variance}}$$

The probability p of the null hypothesis—all means are equal—is based on the F -distribution with $g-1$ and $n-g$ degrees of freedom.

In the first example, the variation of femur length in males and females, we obtain $F = 10.29$. Given that degrees of freedom are 1 and 8, respectively, the above value of F determines that the null hypothesis—there is no difference between femora from men and women—has a probability of 0.01247. This is a very low value (below the usual threshold of 0.05), so we can conclude that sex (the independent variable) has a significant effect on the length of this bone (the dependent variable), and hence we can conclude there is some sexual dimorphism in this population. In the second example, the variation in house shape from four different sites, we obtain $F = 20.45$. Given that degrees of freedom are 3 and 44, respectively, the above value of F determines that the null hypothesis—there is no difference between buildings in different settlements—has a probability of 0.000. We can conclude that spatial variation at a regional scale (the independent

variable) has a significant effect on the shape of buildings (the dependent variable).

One-way analysis of variance coincides with Student's t -test when the number of groups is two. This can easily be proved in the first example. In the second case, we can obtain further insights into the relationship between the regional differentiation of buildings by comparing the means of houses in each settlement pairwise. This is the basis of the Tuckey post-hoc test to find patterns and/or relationships between subgroups of sampled populations that would otherwise remain undetected and undiscovered with the primary result of the analysis of variance. The procedure calculates for each pair the Studentized range statistic:

$$\frac{\text{Largest mean group} - \text{smallest mean group}}{\text{Standard error of the data}}$$

The Tuckey test is essentially a Student's t -test, except that it corrects for the probability of making one or more false discoveries, or type I errors when performing multiple hypotheses tests. In our second example, the Tuckey post-hoc test gives results as shown in Table 3. This indicates that buildings from Settlement 1 are less circular than buildings from Settlement 2, but they have the same circularity as buildings from Settlements 3 and 4. Buildings from Settlement 2 are different from buildings at any other site. Buildings from Settlement 3 and Settlement 4 are also statistically different.

ANOVA models are parametric, relying on assumptions about the normal distribution of the dependent variables for each level of the independent variable(s). This is a very important aspect because the irregularity of a distribution implies the lack of central tendency, and it prevents the use of the mean as a representative of a group. This assumption is frequently violated in archaeology, given the irregularity and uncontrolled nature of data sampling. The user should check

Table 3 Tuckey post-hoc test results for the data in Table 2.

	Settlement 1	Settlement 2	Settlement 3	Settlement 4
Settlement 1	-	0.000	0.348	0.304
Settlement 2	-	-	0.000	0.000
Settlement 3	-	-	-	0.006
Settlement 4	-	-	-	-

via histograms, skewness and kurtosis tests, overall and for each group. If data are not properly symmetric around the arithmetic mean, one should consider a nonparametric test such as the Kruskal–Wallis test.

Another assumption of this test implies the homogeneity of variances, also called *homoscedasticity*. Its opposite, the non-comparability of variances, is referred to as *heteroscedasticity*. This can be checked via Levene's or Bartlett's tests.

Levene's test is based on the calculation of a test statistic W :

$$W = \frac{N - k}{k - 1} \frac{\sum_{i=1}^k N_i (Z_{i.} - Z_{..})^2}{\sum_{j=1}^k N_i (Z_{ij} - Z_{i.})^2}$$

where k is the number of different groups to which the sampled cases belong, N_i is the number of cases in the i th group, N is the total number of cases in all groups, Z_{ij} is the mean of the i th group, $Z_{i.}$ is the mean of Z_{ij} for the group i , and $Z_{..}$ is the mean of all Z_{ij} .

The test statistic W follows an F -distribution with $k - 1$ and $N - k$ degrees of freedom. If the resulting p -value of Levene's test is less than some significance level (typically 0.05), the null hypothesis of equal variances (homoscedasticity) can be rejected and the conclusions of the analysis of variance are reliable.

An alternative to Levene's test is Bartlett's test. If there are k samples with sizes n_i and s_i^2 sample variances, then Bartlett's test statistic is:

$$\chi^2 = \frac{(N - k) \ln(S_p^2) - \sum_{i=1}^k (n_i - 1) \ln(S_i^2)}{1 + \frac{1}{3(k-1)} \left(\sum_{i=1}^k \left(\frac{1}{n_i - 1} \right) - \frac{1}{N - k} \right)}$$

where N represents the number of observations in all samples and S_p^2 is the pooled estimate for the variance. The test statistic was approximately a χ^2_{k-1} distribution. Thus, the null hypothesis is rejected if $\chi^2 < \chi^2_{k-1, \alpha}$ (where $\chi^2_{k-1, \alpha}$ is the upper tail critical value for the $\chi^2_{k-1, \alpha}$ distribution).

When Levene's or Bartlett's tests show significance, one should switch to more generalized tests, free from homoscedasticity assumptions, and sometimes even nonparametric tests, such as the Kruskal–Wallis test (see below).

Note that the larger the sample size, the more robust ANOVA is to violation of these two

assumptions: normality and homoscedasticity (homogeneity of variance). A sample size > 20 for each level of the independent variable is preferred. For small datasets, instead of using the usual F -distribution, a permutation-calculated p seems less prone to type I errors. A permutation test computes if an F value like the value calculated for the case study may appear in 10,000 repeats of a random set. It is an alternative way to check the probability of accepting or rejecting the null-hypothesis. If the permutation p -value is less than the acceptance level (typically 0.05), we can reject the null hypothesis with confidence.

Therefore, when conducting an ANOVA it is always important to calculate the effect size, because with a big enough sample size, any difference in means, no matter how small, can be statistically significant. The effect size tells the archaeologist the importance of observed differences between assemblages or groups. Omega squared (ω^2) is a measure of effect size, or the degree of association for a population. It is an estimate of how much variance in the dependent variable is accounted for by the independent, and hence explanatory, variable. For between-subjects, fixed effects designs, the formula is:

$$\omega^2 = \frac{F - 1}{F + \frac{N - J + 1}{J - 1}}$$

where N is the sample size, J the number of groups, and F is obtained as a result of ANOVA. ω^2 can have values between ± 1 ; if the observed F is less than 1, ω^2 will be negative. Zero indicates no effect. In our second case, we have obtained $\omega^2 = 0.5486$. According to the standard interpretation by Jacob Cohen, this is a large effect. The opposite, a small effect size, can be inferred when the calculated value of ω^2 is around 0.01.

The Kruskal–Wallis test is the nonparametric equivalent of the one-way analysis of variance (ANOVA), with the data replaced by their ranks. Since it is a nonparametric method, the Kruskal–Wallis test does not assume a normal distribution; it can be regarded as a test of dominance between distributions. The null hypothesis is that the sum of ranks of all groups are equal, and the alternative hypothesis is that at least one summed rank of one group is different from the summed rank of at least one other group. When distributions are similar, medians should

be reported rather than means since they (in the form of mean ranks) are what the test is actually comparing.

The test statistic H is computed as follows. For each group the sum of ranks, R_g , as well as the number of observations, n_g , is obtained, and then:

$$H = \frac{12}{N(N+1)} \sum_{g=1}^g R_g^2/n_g - 3(N+1)$$

where n_g is the number of elements in group g , N is the total number of elements, and R_g is the sum of ranks in group g . The significance level is based on the χ^2 distribution, with $k-1$ degrees of freedom. In our second example, the variation of house shape from four different sites in the same region, the assumption of normality is violated in the case of settlements 1 and 3. The assumption of homoscedasticity is also violated, as suggested by Levene's test (p same variance = 0.0065). Given those violations of initial assumptions, ANOVA results can be suspect. As an alternative, we have performed a Kruskal–Wallis test for the same data: $H = 23.22$, for $4-1$ degrees of freedom, p same sum of ranks = 0.000. We can conclude there is a significant difference between sample medians. Dunn's post-hoc test gives the same results as the Tuckey test for the parametric ANOVA.

In a one-way analysis of variance or a Kruskal–Wallis test we compare a single dependent variable with a single independent variable, composed of any number of different levels. A two-way ANOVA refers to an ANOVA using two independent variables. Expanding the examples above, a two-way ANOVA can examine differences in length (the dependent variable) by activity area (independent variable 1) and time (independent variable 2). Two-way ANOVAs can be used to examine the interaction between the two independent variables. Interactions indicate that differences are not uniform across all categories of the independent variables. For example, stone tools found in long-term residential areas may have smaller lengths overall compared with stone tools from occasional hunting camps, and are longer in the Upper Paleolithic compared with the Mesolithic.

Two-way ANOVAs are also called factorial ANOVAs. Factorial ANOVAs can be balanced (have the same number of observations in each group) or unbalanced (having different numbers

of observations in each group). Unequal sized groups can make it appear that there is an effect when this may not be the case.

Researchers have extended ANOVA as MANOVA and ANCOVA. MANOVA stands for the multivariate analysis of variance. MANOVA is used when there are two or more dependent variables. ANCOVA is the term for analysis of covariance. The ANCOVA is used when the researcher includes one or more covariate variables in the analysis.

SEE ALSO: Archaeological Classification; Archaeometry; Assemblage; Compositional Data Analysis; Computer Applications in Archaeology; Craniometry; Descriptive Statistics; Estimating Skeletal Sex; Metrics; Experiment in Archaeology; Exploratory Data Analysis (EDA); Factor Analysis; Geometric Morphometrics; Hypothesis Testing; Lithics Data Quantification; Mathematics; Measurement Theory; Mortuary Analysis; Multivariate Analysis; Nonparametric Statistics; Pottery Data Quantification; Regression and Correlation Analysis; Sampling Theory; Statistics in Archaeology; Stature Estimation; Value or Significance

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Archaeological Classification

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Classification has been crucial to the archaeological enterprise from its inception. Its importance ranges from the pragmatic—a way to arrange artifactual material in an orderly manner—to the analytic—a means to construct a “window” opening onto the lifeway of a past group of people inferred from the traces of their behavior expressed through patterning in artifactual material. From a pragmatic perspective, a classification may be based on the material (see CHROMATOGRAPHY AND ARCHAEOLOGICAL MATERIALS ANALYSIS) from which an artifact is made, its morphological form, its inferred functionality, the technology (see ARCHAEOLOGIES OF TECHNOLOGY) underlying its production, the time period of its occurrence (see DATING IN ARCHAEOLOGY), the cultural context in which it occurs (or is believed to occur), its occurrence together with other artifacts, and so on.

Archaeological classification, in its most basic sense, involves forming classes of artifacts whose members are considered to be equivalent for analytical and interpretive purposes. In this sense, archaeological classification can be thought of as a division of a collection of objects into disjoint and exhaustive classes—an operation known formally as a partition. The rationale for the divisions may range from being empirical, for example when the division is based on properties of the artifacts, to being conceptual, for example when the division is created using constructs developed as part of the archaeologist's understanding of how the material domain integrated with the lifeway of the producers and users of the artifacts that have been recovered.

A classification needs to be rigorous, consistent, and replicable. The choice of one classification over another typically relates to whether the class differences in the selected classification

adequately express the information to be made evident when the classification is used for analytical and other purposes. Under this criterion, using just time-sensitive artifact properties, one might pragmatically construct a chronological classification consisting of a time-ordered (see DATING IN ARCHAEOLOGY) series of artifact classes when the goal is to order sites chronologically by reference to this classification. For a more analytical purpose, such as delineating the presence, form, and importance of social stratification in a past society, the artifact classes might be based on aspects of artifacts pertaining to differences, for example, among social strata.

The multiplicity of possible classifications for the same artifactual material implies the need for criteria that should determine which of several possible classifications may be more appropriate. One such criterion, espoused by William Adams and Ernest Adams (1991), has been to consider that classifications are, essentially, partitions formed pragmatically in accordance with the research interests of the archaeologist. From this perspective, there is no correct classification but only multiple, alternative classifications, each satisfying the partition criterion, and the choice of a particular classification depends on the research goals of the archaeologist.

This pragmatic view of classifications rightly emphasizes that there is no absolute or correct procedure for creating an archaeological classification. Nonetheless, it demotes as incidental to classification the perspective of early twentieth-century archaeologists—from the American Irving Rouse (1939) to the British V. Gordon Childe (1925)—that a classification is not simply a way to order the artifactual material recovered by the archaeologist. It should make evident the cultural context that gave rise to the patterning expressed through a classification. As Robert Dunnell (1971, 132) stated: “*Prehistory assumes that attributes [of artifacts] which are the products of human activity ... can be treated as manifestations of ideas held in common by makers and users of those artifacts*” (emphasis in the original).

Rouse introduced the notion that the ideas held in common by a community of artisans are

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given material form through artifact dimensions, to which he referred as *modes*, and have dimension values or states shared by artisans in their production of artifactual material (see MATERIAL CULTURE). He referred to other artifact dimensions, whose values or states are specific to the individual artisan, as *attributes*. Accordingly, an exhaustive set of artifact dimensions measured over individual artifacts will likely be composed both of modes, on which culturally sensitive classifications are to be based, and of attributes, which represent those aspects of artifacts whose values are specific to the individual artisan. However, which dimensions are modes and which are attributes is not known a priori, and the weakness of this approach to classification has been the lack of a rigorous, objective, and theory-based methodology for distinguishing modes from attributes (but see Read 2007 for such a method). For Childe (1956, 19), the cultural connection is even less detailed and culture (or tradition) is simply the basis for a type: “a type is a type because it is the result of distinct actions all inspired by one and the same tradition.”

Despite not having a satisfactory analytical means for implementing these ideas, the type, perceived as the manifestation of a shared cultural framework, provides, at least conceptually, a way to relate the human modified material remains of a past society to their cultural context. This enables archaeology, as an academic discipline, to position itself as contributing insight, through artifact classification, into the cultural framework of a past society and, by the nature of archaeological material, as introducing a time-depth difficult to obtain through ethnographic fieldwork carried out among living people. The consequence has been that archaeology was seen not just as a historical, but also as an anthropological discipline.

Like the writings of Rouse and Childe, the earlier archaeological literature dealing with classification, especially in North America, was concerned with ways to relate artifactual material to our understanding of human systems. Early to mid-twentieth-century archaeologists who helped frame current-day American archaeological viewpoints regarding artifact classification, such as John Brew, Harry Colton, James Ford, Alfred Vincent Kidder, Alex Krieger, Philip Phillips, Irving Rouse, Albert Spaulding, Jo Ben Wheat, and others, worked from the premise

of classification as a way to make connections between the material properties of artifacts and the concepts and ideas held by their makers and users. As Krieger (1944, 275) put it succinctly, classification provides insight into the “meaning of the myriad works of man.”

One important outcome stemming from this work has been the type-variety system of classification that addressed what had become increasingly evident, especially in American archaeology, namely that the plethora of artifact types being identified as archaeological research became more extensive was not just a sum of independent material instantiations of cultural concepts, but the types often appeared to be linked to one another in the manner of theme and variation. The theme, to use Rouse’s terms, is that of a type defined through modes, variation being represented by alternative forms distinguished through attributes.

The weak point in this view of the role of classification in archaeology has been, and continues to be, its implementation. A crucial difficulty is the double-bind problem that arises from the fact that the means for identifying the cultural dimensions by which the initial heterogeneity in the data brought forward for analysis is to be resolved through classification require already having in hand precisely those cultural dimensions that are to be identified through the classification (Read 2007; 2015). Archaeologists have long recognized that data heterogeneity is problematic; take, for example, the common practice of initially bounding the dataset brought forward for analysis through spatial and temporal boundaries. Creating these boundaries is not done just for analytical convenience, but because of the implicit perception that combining all artifactual material, independently of its spatial and temporal proveniences, into a single dataset leads to analytical obfuscation, not to clarification. Thus, before analysis begins, datasets are circumscribed by reference to spatial and temporal patterns in the data that result from cultural ideas expressed materially through artifacts.

Regardless of theoretical orientation, the general goal of classification is to establish a series of data classes in which the heterogeneity of artifacts in the dataset brought forward for analysis is reexpressed as heterogeneity between internally homogeneous data classes. Through

this transformation, that artifact classes should be culturally valid comes to the fore. Consider that artifacts are initially subdivided according to the kind of material, such as stone, bone, wood, or clay, out of which they have been made or manufactured. Partitioning artifacts by kind of material subdivides the assemblage into artifact classes homogeneous with respect to material and differing among themselves by kind of material. In this manner, the material heterogeneity of individual artifacts is transformed into external class differences among artifact classes that are internally homogeneous (with respect to type of material). The rationale for so doing relates to the fact that the producer's choice of material is not happenstance but reflects cultural (and individual) ideas regarding how the material from which an artifact is made relates to the efficacy with which its intended functionality can be realized. Here functionality may be considered either in its material sense of effectiveness in carrying out a physical task or in its ideational sense of effectiveness in implementing a community-shared cultural ideas system that is expressed, at least in part, through the material properties of artifacts. Artifacts are not made solely in order to carry out material tasks; they are also given particular form and are imbued with properties in order to express ideas and beliefs, hence functionality may be considered ideationally as well as materially. Thus classification connects the cultural domain of concepts and ideas with the material domain of artifacts.

Basing class definitions on the properties of artifacts that reflect the cultural context of the producers gives rise, however, to subjective, extensive definitions that are group-specific, hence spatially and temporally contingent. This subjectivity has led some archaeologists to advocate constructing, in lieu of taxonomies made up of extensive class definitions, paradigmatic classifications based on intentional class definitions expressed through dimension states imposed by the researcher. A paradigmatic classification consists of all possible classes, including vacuous classes, defined through all possible combinations of dimension states, each combination consisting of exactly one state from each dimension. However, for a quantitative variable, the researcher's imposed boundaries for the range of values that define a dimension state introduce subjectivity, unless the imposed widths of boundaries for

the range of values are small in comparison to the scale suitable for expressing numerical variation in a frequency distribution for the mode values through which producers implemented their cultural ideas about artifacts and artifact form. Otherwise, except when there is a uniform distribution, the artifact frequency distribution for the classes of the paradigmatic classification will depend on the choice of the imposed range boundaries used to define the state values for the paradigmatic classification. This means that different boundary choices can change the conclusions drawn from an analysis dependent on those frequencies. It follows that a paradigmatic classification cannot proceed objectively without the double-bind problem of data heterogeneity being solved first; but solving it already produces the basis for a culturally sensitive classification. A means for solving the double-bind problem by recursively identifying homogeneous subsets has been presented by Dwight Read (2007). These homogeneous subsets represent subjective types, not in the sense of distorting subjectivity introduced by the researcher but in the sense of subjectivity introduced through artisan choices in the artisans' production of artifacts. In this manner, objectively determined analytical units suitable for relating the material domain of artifacts, as recovered by the archaeologists, to the ideational domain of past societies, as advocated by the intellectual founders of archaeology, are identified and organized through classifications.

SEE ALSO: Assemblage; Cluster Analysis; Principal Component Analysis; Seriation

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Artificial Intelligence

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Material entities preserved from the past and recognized as cultural assets in the present should be explained by the particular causal structure in which they participated. This cognitive action can be defined in formal terms as the transformation of an incoming sensory vector (the archaeological data) into an appropriate conceptual vector (the explanation), which should be consistent with a hypothetical causal model of the input vector. That is, given a description of archaeologically observable features and a set of already known hypothetical social activities, actions, and/or behavioral models known to the archaeologist, we should assign correct causal explanations to observations (Barceló 2009).

A computer can be programed to carry out this task. The most basic supervised learning algorithms are designed to find a conjunctive description for a single concept *C* that covers positive instances of *C* and that fails to cover negative instances. Thus, we need to determine:

- an initial formulation of a social behavior in the past;
- an object that we know was used in that way, whose visual and nonvisual features have been appropriately quantified;
- an explanation of the association between the behavior and the object (why these particular behavioral mechanics generated the visual/nonvisual appearance of the object);
- some operating criteria;
- a generalization of the object's shape/form that substitutes initial description and is related to the explanation and operating constraints.

In other words, the idea is to program a computer system able to look for common features between positive examples of the known function

to be predicted and common differences between its negative examples. This task is exactly similar to an example of a truth-function learning problem.

In Table 1 the symbol “1” represents a “true” value and the symbol “0” represents a “false” value. Inputs that map onto “true” are treated as positive examples of a particular concept. Inputs that map onto “false” are treated as negative examples (i.e., counter-examples). The process of finding a solution to such a problem is naturally viewed as the process of calculating the *communalities* among positive examples. As such, it is a variation of the philosophical theories seeing *induction* as a process involving the exploitation of similarity. The task of learning possible explanatory functional assignments consists of separating the input vectors, assigning some of them to a known output, from the input vectors that are assigned to one another. We need *training data*, that is, known instances of explanatory concepts, to be capable of predicting the way each explanatory output is connected to each descriptive input.

Basically, this is known as *pattern matching*. Pattern matching is actually a very broad concept. It is useful to distinguish among types of matching. Pattern completion has been defined as the mapping of an incomplete pattern onto a completed version of the same pattern. Pattern transformation is the mapping of one pattern onto a different, related pattern. Pattern association is the arbitrary mapping of one pattern onto another, unrelated pattern. Finally, pattern recognition has been defined as the mapping of a specific pattern onto a more general pattern (that is, the identification of an individual as an exemplar of a class).

A naïve solution would be to list all imaginable “archaeological descriptions” that fit the same “social behavior.” This universal knowledge base would contain all the knowledge needed to “guess” in a rational way the most probable ancient behavior that may have generated the artifact. This way of learning, usually called *case-based learning* in the artificial intelligence literature, is claimed to be a paradigm of the human

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Table 1 The process of calculating the *communalities* among positive examples of a particular concept.

1	1	0	1	1	→	1
1	0	0	0	0	→	0
0	1	1	1	0	→	1
1	1	0	0	1	→	0
0	0	0	0	0	→	?

way of solving complex diagnostic problems in domains like archaeology.

The trouble is that in most real cases, there are infinite observations that can be causally linked to a single action, making them impossible to list by extension. Added complications arise because archaeological observation and explanation are always fraught with uncertainty. From an analytical perspective, this means that it is quite possible that two similar or even identical samples of prior cases will fall into different classes because there may be ambiguity within the learning sample. If many of our samples are ambiguous for a given set of features, we must conclude that these features have poor explanatory power, and no good solution to the problem may be possible with them alone.

Even the most systematic and long-term record-keeping is unlikely to recover all the possible combinations of values that can arise in human work. Thus, archaeological explanation should be transformed into the task of finding some solution that identifies essential patterns in the samples that are not overly specific to the sample data. There is usually a reduced number of material effects of a past behavior that are individually enough (given the right theoretical assumptions) to infer the presence or absence of such behavior. The trick is finding such material clues of past action, in terms of the perceived modifications caused by the same action, preserved until today. Instead of inferring test implications from a target hypothesis and performing a series of experiments, we should focus our attention on formulating mutually exclusive hypotheses about social action in the past and searching for evidentiary traces in the present to discriminate among them.

Machine learning is a discipline in computer science that has created a number of algorithms to deal with this kind of inductive problems.

The huge number of learning algorithms and data-mining tools make it impossible that we can review the entire field in a single paper (Witten, Frank, and Hall 2011; McCue 2014; Zaki and Meira 2014; Aggarwal 2015). Free computer programs like *Weka* (<http://www.cs.waikato.ac.nz/ml/weka/>, accessed November 24, 2017) and *Tanagra* (<http://eric.univ-lyon2.fr/~ricco/tanagra/en/tanagra.html>, accessed November 24, 2017) can be explored to discover how to extract meaning and knowledge from archaeological data.

The best example of these algorithms is a technique known as “neural network” (Barceló 2009; Krawczak 2013; Keller, Liu, and Fogel 2016). For a computing system to be called an “artificial neural network” or “connectionist system,” it is necessary to have a labeled directed graph structure where nodes (representing artificial neurons) perform some simple computations. These nodes are combined into layers, in such a way that the first layer contains descriptions of archaeological observations converted into vectors. For instance, a vector containing its main measurements can describe a pottery vase: maximum diameter, maximum height, circularity index of the shape contour, convexity index of the shape contour, center of gravity, elongation, 3D sphericity, and so on. A hunting site can be formally described using a numeric vector whose components refer to spatial coordinates, chronology, and abundance of particular archaeological categories (wild fauna bones, arrow points, etc.). The final layer of computing nodes or “neurons” contains the explanation. It can be expressed as a categorical value (this vase was a “jar” or it was not; this vase was an “amphora” or it was not; this site was a “specialized hunting station” or it was not). We can give also a probabilistic context to this “explanatory node,” in such a way that its “degree of activation” represents the confidence we have in this particular explanation.

Different “neurons” from the output or final layer represent different “prototypical values” along an explanatory continuum, and respond with graded signals reflecting how close the current exemplar is to their preferred value. Note that what is really being computed is the degree to which one neuron—representing a microfeature of the final concept or prototype—predicts another neuron or microfeature. Thus, whenever

a certain configuration of input features is present, a certain other set of features is also present. The role of neural networks is to provide general parameterized nonlinear mappings between a visual input, for instance, and a set of output explanatory categories. The neural network builds discriminant functions from its neurons or processing elements. Consequently, the pattern of interconnections between “neurons” is represented mathematically as a weighted, directed graph. In this graph, the vertices or nodes represent the information, the links or edges represent the connections between elements, the weights represent the strengths of these connections, and the directions establish the flow of information and more specifically define inputs and outputs of nodes and of the network. Each node’s activation is based on the activations of the nodes that have connections directed at it, and the weights on those connections. To complete specification of the network, we need to declare how the nodes process information arriving at the incoming links and disseminate the information on the outgoing links.

There are two modes in neural information processing:

- training mode
- using mode.

During training, the network “learns” a nonlinear function, associating outputs (hypothetical explanation) with input patterns from a database of experimental data. The network modifies selectively its parameters, so that application of a set of inputs produces the desired (or at least consistent) set of outputs. Training is accomplished by sequentially applying input vectors—for instance, images or 3D scans—while adjusting network weights according to a predetermined procedure. As the network is trained, the weights of the system are continually adjusted to incrementally reduce the difference between the output of the system (the “automatic” explanation) and the desired response (experimental data). During training, the network weights gradually converge to values such that each input vector produces the desired output vector. The network self-adjusts to produce consistent responses. By adapting its weights, the neural network works towards an

optimal solution based on a measurement of its performance. Once trained, a network’s response becomes insensitive to minor variations in its input.

In the using mode, the presentation of an input sample should trigger the generation of a specific prototype or category. It is clear that a single prototype represents a wide range of quite different possible inputs in that it represents the extended family of relevant features that collectively unite the relevant class of stimuli into a single category. Any member of that diverse class of stimuli will activate the entire prototype. In addition, any other input stimulus that is *similar* to the members of that class, in part or completely, will activate a pattern that is fairly close to the prototype. Consequently, a prototype vector activated by any given visual stimulus will exemplify the accumulated interactions with all the possible sources of the same or similar stimuli in proportion to the frequency with which they have been experienced. A prototype, as formed within a neural network, is by definition “general,” in the same sense in which a property is general: it has many instances, and it can represent a wide range of diverse examples. However, this property does not mean that prototypes are universal generalizations. No prototype feature needs to be universal, or even nearly universal, to all examples in the class.

More than an analogy with a universal database, the basis of artificial intelligence methods is the idea of an *associative memory*. This is a device not only storing associations among individual perceptual representations, but also organizing “conceptual” information not directly derived from the senses. Neural networks are used as associative memories. If the associative mechanism runs properly, then the pattern of activation in the output neurons will be the pattern that was originally associated with the cue pattern. Such an associative memory is not limited to the association of only those specific individual objects whose functional properties have been experimented before. If that was the case, the mechanisms underlying archaeological explanation based on artificial intelligence would be of limited use. As archaeologists, we must identify a range of novel data as corresponding to a given type of object. Generalization is part of our ability to identify objects and events. The

capability for archaeological recognition implies then the existence of some previous form of learning, in which the potentially explanatory categories have been created and defined. The goal of recognition is to perform these identifications correctly, in the sense that identification reflects a meaningful property of the world that is independent of the particular data that are being interpreted. A neural network is a kind of computer program that is able to do the same.

Connectionist systems are not simple mechanisms for recording a set of discrete associative links between elements. The explanatory process is one of getting the computer program to duplicate the specific regularities presented in some specific input. It does this, however, only by constructing a particular dynamical system, whose behavior is defined not only over the set of instances ("associations") to which it has been exposed, but also over the full range of possible input (or hidden) states. That is, a "machine" generating an appropriate response to a certain fixed range of inputs is automatically one that generates *some* response to the full range of possible inputs. It will generate the *correct* response to the full range of possible inputs if the training process succeeds in discovering a distributing transformation from input to internal representations, giving the space of internal representations the right kind of intricate hierarchical structure.

In any case, archaeological explanation cannot be reduced to the task of finding the common structure in a given formalized description, because such methods are limited by the natural grouping of the input data, and they are based on restricting knowledge production to finding literal regularities in the input. Such regularities are not generalizable out of the specific limits of the input data used. Explaining *why* archaeological artifacts and built structures have the shape they have or have been found where they have been found must be grounded in an understanding of both the social and natural events that have influenced the presence/absence, alteration, and displacement of the assemblage as a whole. The fact that the performance of some social action *A*, in circumstances *T*, has a probability *P* of causing a change *Y* in some entity *N* (social agent, community of social agents, or the nature itself) is a property of the social action *A*. It is a measurement of the intensity of the propensity,

tendency, or inclination of certain events to appear in determined causal circumstances. Thus, the primary *explanandum* of archaeological theory is social capacities: the capacity to work, to produce, to exchange, to interact, to obey, or to impose something on someone.

In the same way as human archaeologists, an "intelligent" computer program should understand archaeological observables in terms of a priori *affordances* or *capacities* (Gibson 1987). Aristotle introduced such a concept; he called it *potentiality* (to move, or be movable). For each type of observed change in the materiality of archaeological evidences, a specific type of potentiality should be considered. The implementation of such potentialities inside a machine to explain what it "sees" is usually called computer "simulation" of a causal process (DeLanda 2015; Robinson 2014). It is another domain of artificial intelligence theories, techniques, and technologies.

If machine learning methods like neural networks are just inductive approaches, computer simulation is a deductive approach, whose goal is not the generation of particular explanatory hypotheses but the investigation of the mathematically possible development of specific classes of model systems. A computer simulation is basically the computer representation of a "mechanism," representing how social intentions, goals, and behaviors were causally connected in the past. This can be implemented by building a virtual world, that is, a set of surrogates of people, behavior, objects, and environment placed *within* a computer, and acting according to the implemented mechanism. This is a "generative model," that is, a model of a set of mechanisms. By running such a computer simulation, archaeologists can test the accomplishment a tool or a building had in the past to effectively fulfill a specific action or task, which has been formally described and parameterized; that is to say, whether the object or building was used in a certain way and to satisfy a specific goal.

We can even simulate an entire society in terms of autonomous software entities (the agents) having autonomy and "intelligence" to act like people acted in the past, thus taking their own decisions based on computer instructions that mimic the goals of the humans they "imitate" and the state of the world in which they are supposed to be

(Barceló and Del Castillo 2016). Computationally speaking, virtual agents will consist of a body that contains a set of state variables and behavioral instructions. Social activities will be implemented as simple scripts that are initiated and terminated based on rules. We should also include beliefs and goals—perhaps via the creation and execution of a plan. The attributes and behaviors of agents should be “encapsulated” in the agents themselves, not added later “as an afterthought.” Simulated agents act on the grounds of beliefs about world-states that they contribute to and thus modify, and which will be modified by their actions.

History is then computable to the extent that it can be represented algorithmically as the successive states of some determined input → output function. Such a computable system should consist of a set of states, a set of labels representing the agents and the actions, and a transition relation, prescribing for each state the possible “next steps”—that is, what actions can be performed and (per action) what state results. Selecting one state as the root (the initial state) then yields a formal representation of a process.

The emphasis on computability and algorithms imposed by this “artificial intelligence” approach implies a correlated emphasis in formalization, on objectivity, but not necessary on “truth.” Simulating the past is just a way of increasing the explanatory power of historical explanatory models and not necessarily their “truth likeness.” Each one of the resulting “simulations” of a historical trajectory of events can be used both to experiment with a theory of historical behavior (parameters are manipulated to test for predicted differences) and as a demonstration tool (parameters are manipulated to test for predicted robustness). When used experimentally, manipulations are allowed for agent-level parameters to test the global implications of behavioral assumptions in the case of small-scale societies, but also the computer is allowed to manipulate global parameters to test a macro theory about the dynamical implications of social behavior assumptions in the case of more complex societies. Of course, the limit of the approach is the simple design of the economic behavior, in terms of probabilities for economic success.

Artificial intelligence, virtual reality, and reverse engineering help us to define how ancient

objects, buildings, and landscapes were shaped and used in the past, even if we do not have access to any written description by any contemporaneous witness, starting from the identification of the choices made (among the many possible) in a hypothetical reconstruction of the production process (the *cause*). In this way, we can investigate scientifically and explain to wider audiences the effects of social actions, considering alternative explanatory scenarios, where the parameters of possible behaviors can be changed and tested.

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Bayesian Statistics

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Bayesian statistics is a theory for statistical inference. From particular instances (i.e., data), one may wish to infer general characteristics of the problem being studied. This is a case of inductive logic and is the problem of statistical inference in general. The Bayesian theory, once considered “marginal” or “alternative”, is one of the two mainstream statistical approaches for data analysis (the other being the frequentist or classical approach). As opposed to all other approaches, Bayesian inference is based on a formal mathematical theory that builds an interpretation of probability. Although its origins may be traced back to the eighteenth century, the theory was developed in the twentieth century and became of wide use in the last 20 years with the development of suitable numerical methods and with the ever-increasing availability of computer power. Bayesian statistics has since had a great impact in data analysis in archaeology, and is the only current alternative in many statistical problems.

The problem of statistical inference is a part of the problem of induction, which has been extensively studied in philosophy, particularly in the last century. The epistemological approach of Bayesian inference may be taken as skeptic, as opposed to the rather positivistic perspective of the classical, frequentist, statistical approach. Data is taken to modify a *person's* knowledge regarding some related unknowns. This indeed assumes the existence of *a priori* knowledge of the *person* which, after the evidence provided by data, is transformed into *a posteriori* knowledge. *Person* may refer to a particular human being, but in general refers to any group of people acting together to generate common knowledge, and therefore it is better referred to as an *agent*. An agent may be a person, a public or private organization or, for example, a scientific community.

Inherently, inference brings uncertain statements about the world. Bayesian statistics builds a formal mathematical theory to quantify an agent's uncertainty about formally defined unknowns (namely, alternative models for observables) and, in the presence of data, prescribes how to update the agent's *a priori* information to quantify, *a posteriori*, their uncertainty about the unknowns. The Bayesian theory establishes, under certain general assumptions, that uncertainty should be quantified using probability, and to update such uncertain knowledge one should condition on data, commonly using Bayes theorem. If an agent states that the probability of rain tomorrow is 0.1, they are quantifying the uncertainty of the event *rain tomorrow* (which needs to be properly defined: rain where? how much? etc.).

The traditional definition of probability is based on frequencies. In this perspective, if we toss a coin the probability that it lands on “heads” is 0.5, which means that, if we repeatedly toss the coin, on average it will land on heads 50 percent of the throws. In the long run, when the number of tosses tends to infinity, the proportion of heads over tails should be exactly 0.5. And this is the meaning of “the probability of heads is 0.5”. However, this depends on the availability of a set of identically repeatable events (i.e., the coin tosses), which are at least in principle repeatable an infinite number of times. On the other hand, if an agent says that the probability of rain tomorrow is 0.1, this statement must be interpreted in quite a different manner from the frequentist interpretation of the coin probability, since there is only one “rain tomorrow” (no repeatable events). A frequentist interpretation does not make sense in this case, and note in passing that these sorts of probabilistic statements are far more common, interesting and useful, beyond the idealistic scenario of infinite, identical, repeatable events: the probability that a company goes into default is 0.2, the probability that I die in a car accident is 0.05, and so on.

In contrast, the Bayesian definition of probability, in non-formal terms, may be expressed as follows: an agent quantifies their uncertainty

using probability, which is a formal quantitative representation of their current *opinion* of their uncertainty in a given context that, under certain circumstances, may be turned into a *bet*. That is, if the agent's current probability of rain tomorrow is 0.1, this means that the agent will be prepared to bet at most 9 to 1 against rain tomorrow (the fair odds of probability of 0.1). This also sounds fairly reasonable, if viewed, for example, in the context of probabilities, odds and bets in a horse race. However, this same statement is now currently used in natural and social sciences, as well as in industry and technology, and is based on a skeptic epistemological perspective that inferences are only conditionally bound to an agent's context, current opinion and knowledge, currently available data, and so on, these being "scientific" inferences or otherwise. The probabilistic statements of a Bayesian statistical analysis must be interpreted along such lines.

To fix ideas we now turn to a simple example. Suppose we have a test that will output positive (1) or negative (0) for a particular type of archaeological material. If positive, the material is at least 1,000 years old; if negative it is less than 1,000 years old. The test may yield false positives and false negatives, and an analysis of objects of known ages provides the data in Table 1 for the operating characteristics of the test.

Introducing some notation, let T be the random variable representing the result of the test and E the random variable representing whether the object is more than 1,000 years old ($E=1$) or less than 1,000 years old ($E=0$). Therefore E and T may take the two random values 0 and 1. After performing the test, T may turn out to be positive ($T=1$) or negative ($T=0$), and therefore we may view T as a random variable. However, it seems strange or paradoxical to say that the age of the object is random, for example, stating that $P(E=1)=0.8$, the probability of the object

Table 1 Operating characteristics of the age test example (see text), with 95% of true positives and 90% of true negatives.

	Older than 1,000 years	Younger than 1,000 years
Positive test	95%	10%
Negative test	5%	90%

Table 2 Operating characteristics of the test, as stated in Table 1, now written as conditional probabilities.

	$E=1$	$E=0$
$P(T=1 E)$	0.95	0.1
$P(T=0 E)$	0.05	0.9

being older than 1,000 years is 0.8. Certainly, the object has some well-defined age and it is not the case that it "randomly varies" somehow. But, as explained above, this statement should now be put in a Bayesian perspective: 0.8 quantifies our (we, the agent) uncertainty regarding whether the object is older than 1,000 years and, turning 0.8 into odds, we will be prepared to bet 4 to 1 against it being younger. It now seems clear what we mean, and the "randomness" of E is simply a result of our ignorance regarding the object's age: we, the agent, do not know for sure whether E equals 0 or 1. Introducing more notation, let $P(T=1 | E=1)$ be the probability that $T=1$ given $E=1$, that is, the probability that the test turns out to be positive, provided that the object tested is older than 1,000 years (a true positive). From Table 1, we could assume the conditional probabilities in Table 2.

Now, suppose that for a particular object we perform the mentioned test and it turns out to be positive ($T=1$), what may we say regarding the age of the object? One may be inclined to look at the second column of Table 2 and think that it is "likely" that the object is older than 1,000 years. Should we also consider the third column? That is, how do we formally quantify our uncertainty regarding the age of the object in the light of the positive test result?

Note that Table 2 must have some part of the answer, but it seems to be giving the information backwards. In fact, what we are seeking must be $P(E=1 | T=1)$, that is, *the probability that the object is older than 1,000 years given that the performed test result was positive*. This is the *a posteriori* or posterior probability for $E=1$, after observing a positive test $T=1$. It was assumed that we (the agent) had an *a priori* probability $P(E=1)$ for the object being older than 1,000 years before performing the test.

Let's say, as above, $P(E=1)=0.8$. We need to combine all these pieces of information to

Table 3 Calculations of the posterior probability of the object being older than 1,000 years, $P(E = 1 \mid T = 1)$, using Bayes' theorem. Figures are rounded to four digits.

E	1	0	Addition
$P(E)$ (prior)	0.8	0.2	1.0
$P(T = 1 \mid E)$ (likelihood)	0.95	0.1	
$P(T = 1 \mid E) P(E)$	0.76	0.002	0.762 (= $P(T = 1)$)
$P(E \mid T = 1) = P(T = 1 \mid E)P(E)/P(T = 1)$ (posterior)	0.9974	0.0026	1.0

obtain what is required. Bayes' theorem is precisely the tool for doing that. In its simplest form it reads:

$$P(A|B) = P(B|A)P(A)/P(B)$$

That is, we are able to calculate the probability of event A given B , from the reverse probability of B given A . In fact, Bayes' theorem is sometimes called inverse probability. In terms of our age problem, we may translate it to

$$\begin{aligned} P(E = 1 \mid T = 1) \\ = P(T = 1 \mid E = 1)P(E = 1)/P(T = 1) \end{aligned}$$

and by the law of total probability:

$$\begin{aligned} P(T = 1) &= P(T = 1 \mid E = 1)P(E = 1) \\ &\quad + P(T = 1 \mid E = 0)P(E = 0) \end{aligned}$$

providing a means of calculating the required probability. The involved calculations in our simple example are summarized in Table 3. We can see that the resulting *a posteriori* or posterior probability is $P(E = 1 \mid T = 1) = 0.9974$. Compare this with the *a priori* or prior probability $P(E = 1) = 0.8$. *A priori* we were prepared to bet 4 to 1 against the object being younger than 1,000 years, but now, after the test turned out to be positive, we are prepared to bet 384 to 1. This is the essence of a Bayesian statistical analysis.

Certainly Bayesian analyses in archaeology are far more complex than the above simple example. But they all have these ingredients: (1) a model to construct a likelihood, (2) prior knowledge that is coded into a prior probability distribution, (3) computation of the posterior

distribution using Bayes' theorem, (4) display, use and interpretation of the posterior distribution. All these points may involve different levels of complexity and skills, and in particular (3) is commonly very technical (usually involving sophisticated numerical methods such as MCMC). See Buck and Meson (2015) and references therein as a source of several Bayesian analyses in archaeology.

SEE ALSO: Empiricism; Inferential Statistics; Interpretation; Knowledge and Inference; Mathematics; Personhood and Objecthood; Philosophy of Science; Poisson and Binomial Distribution; Positivism; Scientific Practice; Statistics in Archaeology

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Chi-Square Analysis

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Chi-square is a statistical test invented by Karl Pearson in 1904 to deal with significant differences in contingency tables. A contingency table is a way of organizing count data in such a way that the frequency distribution of a qualitative variable is tabulated across the frequency distribution of another qualitative variable. Rows represent the different states of one nominal variable, columns represent the states of another nominal variable, and cells contain the integer counts of occurrences of that specific state (row, column) of the two variables. In archaeology, contingency tables are used to compare different assemblages in terms of the frequency different types are represented in each one. The easiest contingency table is a 2×2 tabulation of the quantity of objects of type X at male and female burials.

	<i>Male</i>	<i>Female</i>
Absence of type X	13	10
Presence of type X	5	6

This table indicates that there are 34 single burials: 18 of them contain the buried remains of a male individual and 16 of them the remains of a female individual. In 5 out of 18 male burials an object of type X has been found; in 13 out of 18 male burials archaeologists have not found any object of this kind. It is the same for female burials. As soon as we introduce additional variables (age, kind of burial, etc.), the complexity of the table increases.

Contingency tables can be used to compare the frequency of different kinds of artifacts or ecofacts in different assemblages, activity areas, layers, or even sites. For instance:

	<i>Assemblage</i>				
	<i>1</i>	<i>2</i>	<i>3</i>	<i>4</i>	<i>5</i>
Cattle	20	2	0	0	1
Ovicaprid	0	45	0	0	1
Pig	22	12	0	0	0
Red deer	0	5	6	15	1
Rabbit	0	0	0	0	2
Wild boar	0	4	8	22	1

In this example, we have cross-tabulated two qualitative variables: spatial variation—represented as differentiated assemblages—and animal taxa. It is important to take into account that count data are not the same as frequencies. If assemblages should be compared, then they should be comparable in terms of spatial extension and temporal duration: You cannot compare burials with sites, or garbage pits with the remains of a store. A depot that had a slow and constant formation process of six centuries will have higher numbers of objects than a small depot that accumulated objects during five years. Because you are cross-tabulating “spatial variation” units with another variable (animal or vegetal taxa, artifact type, etc.), spatial units should have the same spatial extension and temporal duration, if the comparison is to have any reliable interpretation. Furthermore, the dependent variable (type, taxa) should be exhaustive and indeterminate attributes must be avoided. You cannot use categories like “other,” “unknown,” “not assigned,” “undetermined,” and so on. A final remark concerning the conversion of count data into frequency distributions is the problem of fragmentation: If you are comparing assemblages in terms of the number of fragments of objects of different kinds, your interpretation will address taphonomic questions (why fragmentation is different at different spatial or temporal units). It would be preferable to use some index estimating the minimum number of complete objects at each assemblage.

Once the contingency table has been built, and the nature of count data has been discussed,

we can calculate a statistical index to discover if both variables are related or not. This index will compare whether the proportions of count data in the different spatiotemporal units (columns) vary significantly between archaeological attributes (rows).

The first step for calculating the statistical test is the calculation of how count data would be distributed among cells if there were no differences between columns and rows. This circumstance is referred to as *statistical independence*. We should calculate the marginal totals, and calculate each cell frequency as the (column total $\times$ row total)/table total:

	Male	Female	Total
Absence of type X	13 [(18 $\times$ 23)/34 = 12.176]	10 [(16 $\times$ 23)/34 = 10.824]	23
Presence of type X	5 [(18 $\times$ 11)/34 = 5.8234]	6 [(16 $\times$ 11)/34 = 5.176]	11
Total	18	16	34

The second step is the calculation of the difference between observed frequencies and expected frequencies, using the cancellation-of-minus-signs property of multiplication, and averaging this difference using the cell expected frequency.

	Male	Female	Total
Absence of type X	$\frac{(13-12.18)^2}{12.18} = 0.055$	$\frac{(10-10.82)^2}{10.82} = 0.06$	23
Presence of type X	$\frac{(5-5.82)^2}{5.82} = 0.12$	$\frac{(6-5.18)^2}{5.18} = 0.13$	11
Total	18	16	34

The chi-square test is calculated by adding all averaged differences: $0.05 + 0.12 + 0.06 + 0.13 = 0.36$. In other words, a chi-square test is calculated following the equation:

$$\chi^2 = \sum \frac{(\text{observed count} - \text{expected count})^2}{\text{expected count}}$$

The result of this calculation is the chi-square test value, and it should be compared with the value you would obtain in the case where the differences between observed and expected would have arisen simply by chance. In the case

of independence, the computed chi-square value should approximate the value of the theoretical chi-square distribution. This is a theoretical probability distribution that has one parameter: k , a positive integer that specifies the number of degrees of freedom—that is, the amount of variation is explained as generated by random variation alone. Because the chi-square test is a summation of values (residuals) for each cell, the higher the number of cells, the higher the number of terms in the summation and the higher the resulting value. The size of the table (number of cells) is the key parameter to estimate the degrees of freedom of the calculated value. We approximate this number by multiplying the number of rows minus 1 by the number of columns minus 1. In this case, this multiplication equals 1: the smallest contingency table.

Years ago, it was necessary to read a table with critical values in theoretical chi-square distribution, organized by degrees of freedom and probability. The user checked for the corresponding value of $(\text{rows} - 1) \times (\text{columns} - 1)$. Nowadays, any specialized software is able to calculate the “probability” of the null hypothesis (“there is no association between both variables”) for the table at hand based on the chi-square distribution with the same degrees of freedom. If data in the table are very unlikely given that the null hypothesis is true, then the null hypothesis should be rejected. If the data are not unlikely, then the null hypothesis is not rejected. If the null hypothesis is rejected, then the result of the test is said to be significant.

Using the free software Past (<https://folk.uio.no/ohammer/past/>), we obtain for the previous example:

Chi squared			
Rows,		Degrees	
columns:	2.2	freedom:	1
Chi²:	0.36583	p (no assoc.):	0.54528
Monte Carlo p:	0.7184		

A null hypothesis of independence (no association) between the presence/absence of type X in male and female burials has a probability of 0.54528. That is, it seems very probable that there are no differences in the proportion of male and female burials with type X objects. The threshold

0.05 is used to decide whether the differences are considered significant or not. P (*no assoc.*) below 0.05 is expected in the case where differences between rows and columns are so great that they are not the consequence of randomness. P values higher than 0.05 indicate that the difference *may* be the result of random variation, and association between type or taxa and location cannot be established with reliability.

For the second example, bones of different animal taxa found in five different assemblages, the table is bigger, with six rows and five columns. Degrees of freedom are calculated as $(6 - 1) \times (5 - 1) = 20$. The chi-square result and its significance for 20 degrees of freedom are as follows:

Chi squared			
Rows,		Degrees	
columns:	6.5	freedom:	20
Chi²:	277.32	p (no assoc.):	3.372E-47
Monte Carlo p:	0.0001		

A null hypothesis of independence (no association) between animal taxa and assemblage location has a very low probability of being true (3.372×10^{-47}). This is a number near 0. That is, differences among the different assemblages in the proportion of animal taxa are too big to have been generated just by random variation, and we can conclude that assemblages are different because of the social activity that generated the deposition of animal bones in them.

This last result can be misleading because the chi-square test has an important limitation: When there are many cells with near-zero expectation, the chi-square test is mostly noise. In our case, the expected values are:

	Assemblage				
	1	2	3	4	5
Cattle	4.76	11.78	1.59	4.19	0.68
Ovicaprid	9.52	23.57	3.17	8.35	1.35
Pig	7.03	17.42	2.34	6.2	1.01
Red deer	5.59	13.83	1.86	4.92	0.8
Rabbit	0.43	1.02	0.14	0.36	0.06
Wild boar	14.7	36.37	4.9	12.94	2.1

It has been shown that 17 out of 30 cells (57%) with expected values less than 5 can result in a loss of statistical power: a tendency not to reject a false null hypothesis (“there is no association between both variables”). The problem with the expected frequencies less than 5 is that the test gives larger values with more frequency than the corresponding chi-square distribution under the null hypothesis. Then we may have overestimation of statistical significance for small data, and potentially important results can be missed.

In the case of fourfold tables (2×2), a chi-square test is inappropriate if the total of the table is less than 20, or if the total lies between 20 and 40 and the smallest expected (not observed) value is less than 5. In contingency tables with more than one degree of freedom, it is inappropriate if more than about one-fifth of the cells have expected values less than 5 or any cell an expected value of less than 1. In those circumstances, *exact* p values can be calculated by simulating very many contingency tables (from 10,000 to 100,000), with the same sample size, and verifying the null hypothesis. Then we repeat the chi-square test for all those simulated cases and count the number of times a value like the one we have calculated for the data may arise under the null hypothesis. This method is called *Monte Carlo simulation*. In our example, Monte Carlo p is higher than the usual asymptotic approximation, but still under the 0.05 threshold, indicating that differences are significant, even in the presence of many expected frequencies under 1.

If calculated p (*no association*) value is less than a chosen threshold for significance level, then we usually reject the null hypothesis—that is, accept that the sample gives reasonable evidence to support the alternative hypothesis: there are differences between assemblages, and hence the archaeological attribute contributes to differentiate spatiotemporal depots. It does *not* imply a “meaningful” or “important” difference; that is for the archaeologist to decide when considering the real-world relevance of the chi-square result. The choice of significance level at which we usually reject the null hypothesis is arbitrary. Most authors refer to statistically significant as $p < 0.05$ and statistically highly significant as $p < 0.001$ (less than one in a thousand chance of being wrong).

There are two types of false conclusions that can be committed when interpreting chi-square test results. They are known as type I error and type II error. A type I error occurs when one concludes that a statistical difference in the proportion of different contents exist between assemblages or spatiotemporal units but this conclusion is empirically wrong. Assuming the null hypothesis is true, the probability of a type I error for any given comparison is the p level. In the vast majority of cases, archaeologists concern themselves with avoiding a type I or alpha error. However, many researchers are unaware that the use of such alpha corrections actually reduces statistical power and increases the likelihood of a type II or beta error (i.e., failing to reject the null hypothesis when the null is false). For instance, consider these two examples:

	Male	Female
Absence of type X	32	28
Presence of type X	17	31

Chi-square test = 3.45; p (no association) = 0.063; Monte Carlo p (no association) = 0.08.

	Male	Female
Absence of type X	5	1
Presence of type X	0	4

Chi-square test = 6.66; p (no association) = 0.009; Monte Carlo p (no association) = 0.04.

In the first case, we cannot reject the null hypothesis, because the probability of committing a type I error is higher than the usual threshold of 0.05. However, the numbers in the table seem to be quite similar, and the probability of the null hypothesis relatively low. Are we incorrectly retaining a false null hypothesis (a “false negative”)? In the second case, differences seem to be clear in the table, but the probability of the null hypothesis is even lower, well below the threshold of statistical significance, and we have no statistical basis for rejecting it, although the sample size is also quite small. Are we incorrectly rejecting a false null hypothesis (a “false positive”)?

The probability of committing a type II error gets smaller as the sample size gets larger. To solve this problem, we have to evaluate the *effect size*, that is, the strength of a phenomenon. Statistical power is a function of three basic factors: the alpha level, sample size, and effect size. In general, larger sample sizes and larger effect sizes lead to greater statistical power. We should be concerned about the relationship between sample size and effect size in determining the statistical power of the association between the two variables.

One of the more popular measures of effect size has been the correlation coefficient. In the chi-square case, a measure of the intensity of association like Cramér’s V can be calculated to guide the user in deciding whether a relationship is important and worth pursuing.

Cramér’s V is computed by taking the square root of the chi-square statistic divided by the sample size and the minimum dimension minus 1:

$$V = \sqrt{\frac{\chi^2}{N \cdot m}}$$

where N is the total number of observations in the table, and m is the minor value of rows – 1 or columns – 1.

Cramér’s V varies between 0 and 1. Close to 0 it shows little association between variables. Close to 1 it indicates a strong association. V values around 1 are expected when there is perfect association. In our examples:

$$V = \sqrt{(3.45/108 \times 1)} = 0.18$$

$$V = \sqrt{(6.6/9 \times 1)} = 0.85$$

Cohen (1988, 25–27, 79–80) provides the following ranges for interpreting the effect sizes in Cramér’s V (depending on the complexity of the contingency table, effect sizes may vary):

Degrees of freedom	Small	Medium	Large
1	0.10	0.30	0.50
2	0.07	0.21	0.35
3	0.06	0.17	0.29
4	0.05	0.15	0.25
5	0.04	0.13	0.22

In the first case, effect size is low-to-medium, and therefore we cannot take a final decision on

gender differentiation based only on available data. In the second case, although the sample size is much smaller, effect size is larger, and the probability of making a type II error diminishes.

Effect size is simply a way of quantifying the size of the difference between two groups. This index emphasizes the size of the difference rather than confounding this with sample size. By placing the emphasis on the most important aspect of the study—the size of the effect—rather than its statistical significance (which conflates effect size and sample size), it suggests a more scientific approach to the accumulation of knowledge. For these reasons, effect size is an important tool in reporting and interpreting the effectiveness of chi-square analysis.

Once we know the actual sample, effect size, and probability of committing a type I error, we can calculate the statistical power of the test using two binomial distributions (Oyeyemi et al. 2010). We can use the G*Power 3 free software (<http://www.gpower.hhu.de/>) (Faul et al. 2007). In the first case, we obtain Power ($1 - \beta$ err prob) = 0.4960273. In the second case, Power ($1 - \beta$ err prob) = 0.4277703. The probability of committing type II errors is relatively high in both cases. Results are suspect, in the first case because the effect size is very low, and in the second case because the sample is too small.

SEE ALSO: Archaeological Classification; Archaeometry; Assemblage; Compositional Data Analysis; Computer Applications in Archaeology; Correspondence Analysis; Discrete Traits; Exploratory Data Analysis (EDA); Hypothesis Testing; Lithics Data Quantification; Mathematics; Measurement Theory; Mortuary Analysis; Multivariate Analysis; Nonparametric Statistics; Pottery Data Quantification; Quantification and Social Life; Sampling Theory; Statistics in Archaeology; Value or Significance

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Cluster Analysis

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Introduction

Cluster analysis (CA) is a statistical methodology within the area of multivariate statistical analysis (see *MULTIVARIATE ANALYSIS*) mainly used to classify a set of objects into groups based on multiple measurements that are available for each item. The resulting groups, called clusters, are constructed in such a way that similar objects, with respect to their measurements, belong in the same cluster, and dissimilar objects belong to different ones.

Typically, cluster analysis is implemented for a set of objects that is heterogeneous or else comes from different populations, but no previous information about the number of groups or the object membership is available (in contrast, see *SUPERVISED PATTERN RECOGNITION*). The derived clusters will ideally capture the existing heterogeneity, and each cluster will correspond to a subpopulation. If the data set is homogeneous, the methodology will result in a single group.

The need to classify observations of a dataset into groups is essential and applications of CA can be found in almost every scientific area. Clustering can be a part of the exploratory analysis of the data (see *EXPLORATORY DATA ANALYSIS (EDA)*), especially in high dimensional data or large samples. In those cases, the derived smaller number of groups can (1) facilitate summarizing the information included, (2) provide a description of the data at group level, and (3) find patterns or differences among observations. In other cases, clustering is itself the final goal of the analysis.

Scientific topics with significant contributions in the literature are botany, biology, and ecology within the natural sciences area; archaeology, psychology, sociology, criminology, and linguistics within the behavioral and social sciences;

genetics and clinical diagnosis in medicine; pattern recognition and artificial intelligence in engineering and political science; and marketing in information sciences. The numerical methods used for classification appear under different names in the literature, depending on the area of application, for example, taxonomy, segmentation, Q analysis, and unsupervised pattern recognition. Cluster analysis is the generic name that includes all different approaches and techniques aiming to identify the existing subpopulations in a set of objects.

A brief description of each of the main CA approaches is provided in the next section. For a review of techniques, see Cormack (1971) and Baxter (2006).

Typically, CA is implemented in an $n \times p$ matrix of data measurements, where n is the number of objects to be classified and p the number of variables included in the analysis as relevant to the classification criterion. Variables can be continuous or categorical, and most classification techniques can handle mixed type data. Examples of clustering problems in archaeology and variables that may be included in the analysis are:

Example 1. Assume, as the clustering problem, the identification of groups among a set of archaeological findings (e.g., ceramics or glass) based on their chemical composition (see *COMPOSITIONAL DATA ANALYSIS AND POTTERY DATA QUANTIFICATION*). Variables that may be included in the analysis are the measurements of the archaeological findings on selected chemical elements. The derived groups will contain the specimens with similar chemical compositions.

Example 2. Clustering may assist in revealing information on the provenance of marbles used in ancient architecture and sculpture. The selected variables can be geochemical composition (continuous variables) and petrographic analysis consisting of the mineralogical composition of the marbles after microscopic examination. The mineralogical composition variables are categorical and provide

the presence or absence of certain minerals (e.g., dolomite, quartz, and mica), and the levels (low, medium, or high) in the positive case. The resulting groups will represent marbles with similar chemical compositions and petrological properties.

Example 3. To find common authorship among texts, the variables that represent the measurable features of the texts, such as frequency of use of certain words, length of words or sentences, vocabulary, punctuation, and so on, can be included in a cluster analysis. Variables in this example are also of mixed type.

Clustering methodologies and techniques

A wide range of clustering techniques is available in the literature and quite different approaches have been proposed for the problem of CA. Clustering techniques can be categorized into three main classes, in terms of how they try to find the groups in the data: (1) hierarchical clustering; (2) optimization or partitioning; and (3) model-based clustering techniques.

In hierarchical clustering techniques, the process of finding groups in the data consists of an algorithm. The algorithm can initiate from the situation where the n observations form n different clusters and proceed by merging observations or smaller groups in intermediate stages, until all observations are located in one single group. The corresponding methods are called *agglomerative hierarchical clustering methods*, probably the most widely used CA methods in applications. The alternative starting scenario is the reverse, that is, the algorithm initiates from one group which contains all n observations and proceeds by partition of the data into finer groups until the opposite extreme situation, with n single-member groups, is reached. The corresponding methods are called *divisive hierarchical clustering methods*.

In both types of hierarchical clustering, the decision to merge or partition is made based on a proximity measure (see DISTANCE AND DATA TRANSFORMATION) calculated for all possible pairs of objects (observations or groups) at every step of the algorithm. The output of a hierarchical clustering method will provide a sequence of hierarchy in merging or partitioning,

the graphical representation of which is called a *dendrogram*. Figure 1(a and b) shows some typical dendrograms. The proximity (or similarity) measure is defined in association with the type of variable. For continuous interval scale variables, any distance metric can be used as a measure of dissimilarity. The $n \times n$ matrix whose elements are the distances between all possible pairs of observations is called the dissimilarity matrix, usually denoted as D . Denoted by x_{im} , the (i,m) element of the data matrix ($i = 1, 2, \dots, n$, and $m = 1, 2, \dots, p$) and d_{ij} the elements of matrix D , Table 1 lists the most widely used distance metrics as a measure of dissimilarity for continuous variables.

For binary variables or categorical ones with more than two levels, the similarity measures represent the degree of agreement between the two subjects with respect to their answers over the range of categorical variables. Table 2 gives some of the best-known similarity measures—also called similarity coefficients—for a data matrix consisting of p binary variables, where a is the number of variables out of p for which i and j observations occur simultaneously (presence of the particular characteristic), and b , c , and d are the numbers of presence-absence, absence-presence and absence-absence occurrences respectively. For categorical variables with more than two levels, each level is treated as a binary variable. An important distinction, and an issue that needs to be considered before the selection of a similarity measure, is whether the negative (0–0) agreement of two observations in a variable is informative about the association and has to be incorporated in the measure or not. If $s(i, j)$ stands for the similarity measure, the corresponding dissimilarity degree is defined as $d(i, j) = 1 - s(i, j)$.

For ordinal categorical variables, the same measures as in the case of interval scale variables can be used, implemented to the observation ranks r_{im} instead of the observation values x_{im} , $i = 1, 2, \dots, n$ and ($m = 1, 2, \dots, p$). Moreover, the use of

$$Z_{im} = \frac{r_{im} - 1}{M_m - 1}$$

where M_m is the highest rank for each variable m is often used in order to transform the measurements to the (0,1) interval. For ratio variables,

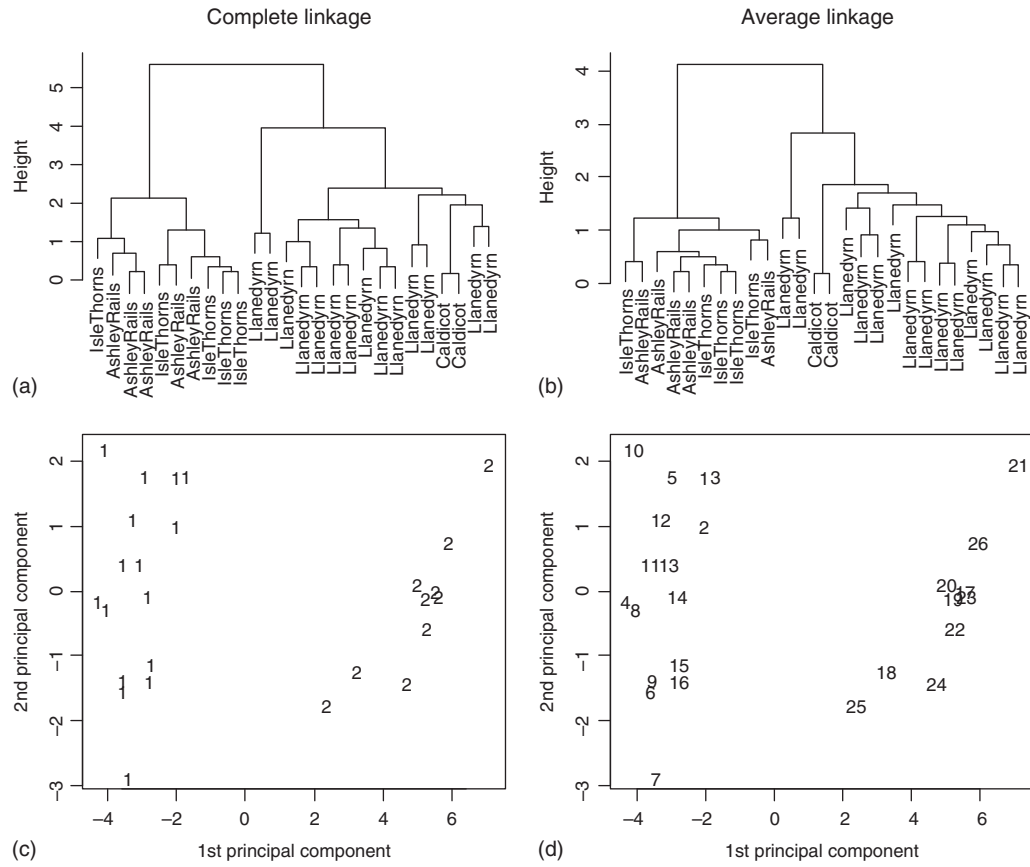


Figure 1 Dendrograms and clusters of pottery data plotted on the first two principal components.

Table 1 Distance measures for continuous variables.

Measure	Definition
Euclidean	$d_{ij} = \sqrt{(x_{i1} - x_{j1})^2 + (x_{i2} - x_{j2})^2 + \dots + (x_{ip} - x_{jp})^2}$
Squared Euclidean	$d_{ij} = (x_{i1} - x_{j1})^2 + (x_{i2} - x_{j2})^2 + \dots + (x_{ip} - x_{jp})^2$
City block or Manhattan	$d_{ij} = x_{i1} - x_{j1} + x_{i2} - x_{j2} + \dots + x_{ip} - x_{jp} $
Minkowski	$d_{ij} = \sqrt[m]{(x_{i1} - x_{j1})^m + (x_{i2} - x_{j2})^m + \dots + (x_{ip} - x_{jp})^m}$
Maximum or Chebyshev	$d_{ij} = \max_k x_{ik} - x_{jk} $
Pearson	$d_{ij} = (1 - \phi_{ij}) / 2$, where ϕ_{ij} is the Pearson correlation between data vectors $\mathbf{x}_i$ and $\mathbf{x}_j$

Table 2 Similarity measures for categorical variables.

Measure	Definition
Simple matching	$s(i, j) = \frac{a + d}{a + b + c + d}$
Jaccard	$s(i, j) = \frac{a}{a + b + c}$
Rogers and Tanimoto	$s(i, j) = \frac{a + d}{a + 2(b + c) + d}$
Anderberg or Sokal and Sneath	$s(i, j) = \frac{a}{a + 2(b + c)}$
Sokal and Sneath	$s(i, j) = \frac{2(a + d)}{2(a + d) + b + c}$
Gower and Legendre	$s(i, j) = \frac{a}{a + 0.5(b + c)}$

a log transformation allows, the measurements to be treated as an interval scale. For mixed type data, where variables of various types are included in the clustering problem, a number of similarity coefficients have been proposed in the literature, with Gower's coefficient the most widely used in practice. The majority of the (dis)similarity measures in Tables 1 and 2 are implemented in standard statistical packages.

Following the choice of the (dis)similarity measure between observations, the second important component in hierarchical clustering is the measure of inter-cluster (dis)similarity, known as linkage. Based on the (dis)similarity measure adopted for observations, linkages determine how this measure will be used in order to define the distance (or similarity) between two groups of observations. This definition will be needed for calculations in all intermediate steps of the hierarchical clustering algorithm. Table 3 lists the most frequently used agglomerative hierarchical linkages.

In conclusion, the main features of hierarchical clustering are that no assumption is made about the distributions of the variables (see NONPARAMETRIC STATISTICS), it is implemented with the help of (dis)similarity measures, the output provides the complete hierarchy in clustering, and any movement (merge or split) at a certain step of the algorithm will not be revised in future steps. Data transformation

(see DISTANCE AND DATA TRANSFORMATION) or different weights per variable during the dis(similarity) measure calculation may also be implemented. Altogether, a wide selection of techniques result as an outcome of all possible combinations of (dis)similarity measures, linkages and, moreover, transformation and weighting. Not all possible clustering techniques produce the same clustering. Their performance depends on the data, how clear the clustering is, the form of the clusters (shape, orientation), the size of the existing groups, and so on. For a more detailed discussion on this topic, we refer to Everitt, Landau, and Leese (2001, chapter 4). An application of hierarchical clustering is provided below.

Optimization or partitioning clustering techniques are characterized as nonhierarchical, and the basic idea behind them is the partition of the observations into groups so that an optimization criterion is accomplished. This criterion attempts to numerically capture the quality of the proposed clustering. Different optimization criteria have been proposed, with the majority of them exploiting—in different ways—the within- and between-cluster measures of dispersion when the observations are allocated into clusters. Let k stands for the number of clusters at a certain step and x'_{ij} is a reallocation of measurements x_{ij} in the data matrix so that i in x'_{ij} stands for the group the observation is assigned to ($i = 1, 2, \dots, k$) and j is the number of the observation in group i , $j = 1, 2, \dots, n_i$, and n_i is the size of group i . If, moreover, $\bar{x}'_i$ stands for the centroid of group i and $\bar{x}$ is the centroid of the complete data, the matrices:

$$W = \frac{1}{n - k} \sum_{i=1}^k \sum_{j=1}^{n_i} (x'_{ij} - \bar{x}'_i) (x'_{ij} - \bar{x}'_i)'$$

$$B = \sum_{i=1}^k n_i (\bar{x}'_i - \bar{x}) (\bar{x}'_i - \bar{x})'$$

denote the matrices of within- and between-clusters dispersion, respectively. The summation $W + B$ is the matrix of total dispersion of the data, which is independent of the specific grouping. The most well-known optimization methods suggested in the literature and used in practice are minimization of $\text{trace}(W)$, minimization

Table 3 Agglomerative linkages.

Linkage	Definition of inter-group distance, d , of groups A and B
Single Linkage or Nearest Neighbor	$d(A, B) = \min_{\substack{i \in A \\ j \in B}} d(i, j)$
Complete Linkage or Furthest Neighbor	$d(A, B) = \max_{\substack{i \in A \\ j \in B}} d(i, j)$
Average Linkage	$d(A, B) = \bar{d}, \text{ where } \bar{d} \text{ is the average distance:}$ $\bar{d} = \frac{1}{n_A n_B} \sum_{i \in A} \sum_{j \in B} d(i, j)$ where n_A, n_B are the group sizes of A and B respectively.
Centroid	$d(A, B) = d(\bar{x}(A) - \bar{x}(B))$ where $\bar{x}(A)$ is the point: $\bar{x}(A) = \frac{1}{n_A} (x_1(A), x_2(A), \dots, x_p(A))$ and is called the centroid of group A.
Ward's	The increase in total error sum of squares (ESS) the merger of A and B will cause. If d_e is the Euclidean distance, the ESS of a group U with centroid $\bar{x}(U)$ is defined as: $\text{ESS}(U) = \sum_{i \in U} d_e(x_i - \bar{x}(U))$

of $\det(W)$, and minimization of $\text{trace}(BW^{-1})$. The method of minimizing the trace of W is not scale-invariant and may impose spherical groups. Minimizing the $\det(W)$ is equivalent to the maximization of the $\det(T)/\det(W)$ criterion. Both methods of minimizing the $\det(W)$ and minimizing the $\text{trace}(BW^{-1})$ are scale-invariant, they may impose the same shape on clusters (although not necessarily spherical), and they also may impose the same number of objects per cluster. For a detailed description, see Everitt et al. (2001, chapter 5) and Baxter (2015, chapter 8). Assuming an optimization criterion, the steps of the algorithm towards the derivation of the “best” clustering are:

- Step 1.* Assume a number of groups k and find an initial partition for the data (it may be derived from a hierarchical method).
- Step 2.* Recalculate the optimization criterion when each observation of a group is located to another.

Step 3. Accept the movement that optimizes the criterion.

The k -means method, probably the most widely used nonhierarchical method, belongs to the same category of clustering methods. It is equivalent to the minimization of $\text{trace}(W)$ method under some regularity conditions.

Model-based CA methods are those where a probability model is assumed for the data, and derivation of the clustering results as a part of the parametric inference of the model (see INFERENCE STATISTICS). More specifically, a finite mixture model (see, among others, McLachlan and Basford 1987) is assumed to describe the data. Each of the existing groups in the data is considered to correspond to one of the mixture components. Mathematically the model is defined as:

$$g(\mathbf{x}; \mathbf{w}, \boldsymbol{\theta}) = \sum_{i=1}^k w_i f_i(\mathbf{x}; \boldsymbol{\theta}_i)$$

where $\mathbf{x}$ is a p -dimensional random vector, f_i the distribution that corresponds to component i

with θ_j their parameter $\theta = (\theta_1, \theta_2, \dots, \theta_k)$ and $w = (w_1, w_2, \dots, w_k)$, the weights of components $\left(\sum_{i=1}^k w_i = 1\right)$.

For the purpose of clustering, the finite mixture model of multivariate normal distribution is frequently used in the case of continuous data. For this instance, $\theta_j = (\mu_j, \Sigma_j)$ where μ_j is the mean vector and Σ_j is the variance-covariance matrix of component j . For any given k , estimating the unknown parameters of the model (see INFERENCE STATISTICS) provides an identification of the distribution components. Each observation is then assigned to a group based on the posterior probabilities calculated for each component distribution. Other distributions besides multivariate normal can also be considered for continuous data, and mixtures of discrete multivariate variables are suitable for categorical data.

The probabilistic approach for CA is (1) computationally demanding, (2) requires hypotheses made about the data and structure of groups, and (3) is more informative with respect to the derived clusters and their properties. Computer and statistical packages are currently available (see below).

Other methods of clustering, such as fuzzy clustering, simulated annealing, self-organizing maps, and so on, are also available (e.g., Baxter 2006).

Application

The dataset chosen for the application consists of chemical measurements of 26 artifacts (pottery) found in four different sites in the United Kingdom (see POTTERY DATA QUANTIFICATION). They form a subset of the data presented in Tubb, Parker, and Nickless (1980), and they are also discussed in Hand et al. (1993). The measurements are available in the “car” (companion to applied regression) R package.

The data matrix is a 26×6 matrix where the first column is a label variable taking four values and indicating the location from which the samples are derived. Analytically the values are: Llanedyrn, Caldicot (two sites near Cardiff; samples 1:16), IsleThorns and AshleyRails (two

sites near the New Forest; samples 17:26). The remaining five columns represent the composition of the samples regarding five chemical elements included in the analysis.

The two geographical locations exhibit great dissimilarity in pottery production, a fact that CA based on measurement of the five chemical elements can reveal. Figures 1a and 1b present the dendrogram of hierarchical CA on standardized data using complete and average linkage respectively. The two geographical locations, as expected, are clearly separated and represented by two distinct clusters according to both linkages. Using principal component analysis (see PRINCIPAL COMPONENT ANALYSIS) for the five chemical elements, a plot in two dimensions of the suggested grouping is possible based on the first two principal components. Figure 1c gives the plot of the resulting grouping after labeling as “1” and “2” the groups with samples from near Cardiff and the New Forest respectively. The difference between the two groups with respect to their chemical composition is apparent. Group 1 from the Cardiff area has negative (standardized) scores in the first principal component, while group 2 has positive scores. Figure 1d is the same but using the samples’ row numbers as labels.

Model-based clustering has also been implemented to data using Fraley and Raftery’s (2002) R package “mclust”. A normal distribution mixture model is fitted and a two-component model is suggested as the best model. The components correspond exactly to the groups obtained from hierarchical methods. More analytically, the best model is the diagonal, varying volume and shape (VVI), that is, the variance-covariance matrices of the two components are diagonal, but not equal.

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Compositional Data Analysis

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Where the relevant information is not about the amount of each part that is being determined, but about the portion of such a part from the total amount, this is referred to as compositional data. These data naturally arise from a large number of situations in archaeological studies. These deserve particular consideration because most of the statistics are misleading or inapplicable. Determining the chemical composition of an archaeological object is, for example, one of these cases. In this case, analytical techniques (see CHEMISTRY IN ARCHAEOLOGY) are used in order to determine the concentration of an element, or an isotope, in a given sample. This type of analysis enumerates or counts the number of each type of atom in a sample (see MEASUREMENT THEORY). Counting is not expressed in absolute numbers, for example, in the total number of atoms existing in the sample under study. On the contrary, the result is given in relative numbers (usually in % or ppm, parts per million). Thus, 2.50% (in mass %) of Fe is in all cases lower than 5.00%. However, if the first concentration corresponds to the iron content of a Roman amphora, while the second one corresponds to the iron content of a small Roman cup of Terra Sigillata, this might not be the case in absolute amounts (in mass). Considering that a typical amphora weight is around 25 kg, the amount of iron in such an amphora would be 625 g. However, the cup could weigh around 100 g, with an iron content of just 5 g. Thus, when we are interested in compositional data, we are not interested in absolute amounts (i.e., the actual mass). Instead, we are interested in proportions of such amounts (i.e., the relative mass). Similarly, when we are interested in knowing the frequencies of petrographical features (e.g., matrix, pores, inclusions

or different types of inclusions; see OPTICAL MICROSCOPY), the portions of different types or classes of pottery in different assemblages (see ARCHAEOLOGICAL CLASSIFICATION and ASSEMBLAGE), or, when examining forms of objects, differences related to shape regardless of size (see GEOMETRIC MORPHOMETRICS), we are also interested in proportions of the total amount and not in the actual amounts.

Compositional data analysis, dealing with the analysis of portions, encompasses two different geometries that exhibit similar characteristics, but also clear differences. In Figure 1 we can see three different points, $A1 = (16.66, 16.66, 16.66)$, $A2 = (33.33, 33.33, 33.33)$ and $A3 = (66.66, 66.66, 66.66)$, represented in a three-dimensional Euclidean space. Since their coordinates are different, they are placed in different parts of this space and they represent different entities. Each point is expressed as a vector with three real numbers; therefore this space is called a real vector space in three dimensions ($\mathbb{R}^3$). This Euclidean vector space has two basic operations:

- Vector addition: the addition of two vectors $\mathbf{x}$ and $\mathbf{y}$ is the element-wise sum of their values and it corresponds to translation. Thus, our three points $A1$, $A2$ and $A3$ points can be equally displaced two units along the x axis just by adding the vector $\mathbf{u} = (2, 0, 0)$ to them.
- Scalar multiplication: the multiplication of a vector $\mathbf{x}$ by a scalar (a real number) a is the multiplication of its corresponding values by this scalar. The result is a new vector which is a times scaled compared with the original. For example, vector $A2$ is twice vector $A1$, because it is the result of multiplying vector $A1$ by the scalar 2.

The Euclidean vector space is further equipped with the inner product that produces a scalar by adding the result of an element-wise multiplication of two vectors. Let vector $\mathbf{x} = (x_1, x_2, x_3)$ and vector $\mathbf{y} = (y_1, y_2, y_3)$, then $\langle \mathbf{x}, \mathbf{y} \rangle = (x_1 y_1 + x_2 y_2 + x_3 y_3)$ is their inner product. The importance of the inner product is that it induces

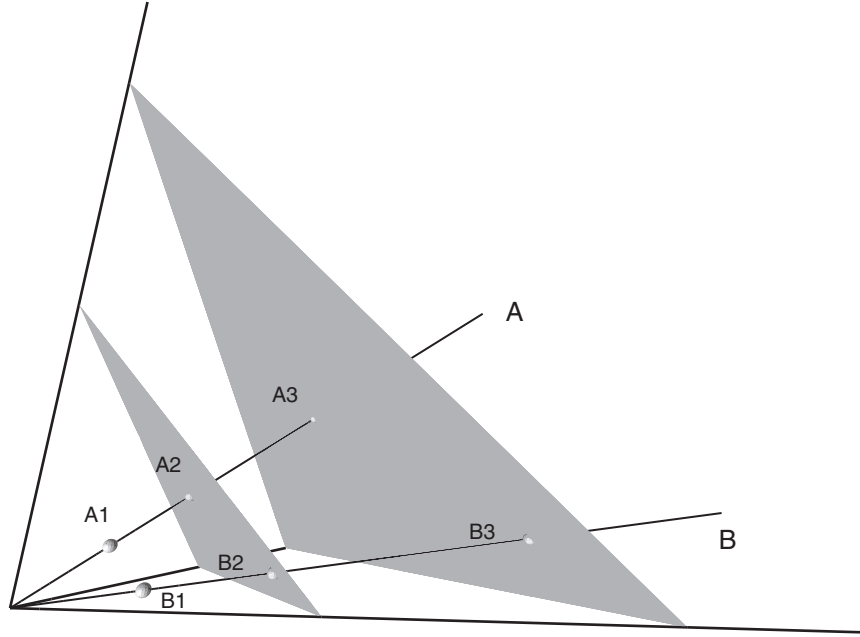


Figure 1 Three-dimensional scatterplot showing the points A1, A2 and A3 as representations of the projective point A, and the points B1, B2 and B3 as representations of the projective point B. Two simplices (for $k = 100$ and $k = 200$) are also displayed.

a Euclidean norm and a Euclidean metric. The former is the square root of the inner product of a vector with itself (i.e., $\|\mathbf{x}\| = \langle \mathbf{x}, \mathbf{x} \rangle^{0.5} = (x_1x_1 + x_2x_2 + x_3x_3)^{0.5}$; exponentiation to 0.5 is equivalent to taking the square root). The latter is the norm of the subtraction of two vectors (i.e., $d_{\mathbf{x},\mathbf{y}} = \|\mathbf{x} - \mathbf{y}\| = \langle \mathbf{x} - \mathbf{y}, \mathbf{x} - \mathbf{y} \rangle^{0.5} = ((x_1 - y_1)^2 + (x_2 - y_2)^2 + (x_3 - y_3)^2)^{0.5}$) (see DISTANCE AND DATA TRANSFORMATION). Finally, the inner product also enables us to define the angle between vectors, which is the arccosine of their inner product, divided by the multiplication of their norms. This structure of Euclidean vector space is extended in n -dimensional space (for more than three dimensions) in what is called the Hilbert space, and is the structure that supports most of the statistical methods usually employed. Therefore, statistical methods are usually designed to work with data that can be handled by such a structure (see DESCRIPTIVE STATISTICS; LINEAR MODELS; and MULTIVARIATE ANALYSIS).

If we consider the previous vectors **A1**, **A2** and **A3** from their portions, by dividing the components by their total amounts, we find out that the three of them represent exactly the same values,

that is, the same composition $[0.33, 0.33, 0.33]$. In Figure 1, the three points are on the same line A. They are no more different entities, just different representations of the same point, because what we understand as a line in Euclidean geometry (line A), is just a point in projective geometry (also called an equivalence class). This projective point can then be represented by an infinite number of possible homogeneous coordinates (indicated by the use of square brackets), and this property that all Euclidean points in an equivalence class represent the same composition is called scale-invariance:

$$\begin{aligned} A &= [16.66, 16.66, 16.66] \\ &= [33.33, 33.33, 33.33] \\ &= [66.66, 66.66, 66.66] \end{aligned}$$

In projective geometry, because of the scale-invariance, the previously defined scalar multiplication does not apply: neither the norm nor the Euclidean distance or the translation operation, precluding the use of common statistical techniques on compositional data. Moreover,

these homogeneous coordinates can be dehomogenized by dividing all components by one of them (e.g., $[x_1/x_3, x_2/x_3, x_3/x_3] = [x_1/x_3, x_2/x_3, 1]$). This way, all possible representations of a projective point, or compositional class, produce a unique representation which is called the canonical form. Since all distinct projective points will have the value 1 in the same component, all projective points will be uniquely represented by $(x_1/x_3, x_2/x_3)$ without any loss of information. Because of that, the real projective space has one less dimension ($\mathbb{RP}^2$) than the corresponding real Euclidean space.

Translation of one compositional class to another is performed by the operation called *perturbation* ($\oplus$), that is, by an element-wise multiplication of a given vector by a perturbing one. Let $\mathbf{u} = (2.4, 0.3, 0.3)$, a perturbing vector; $\mathbf{A1} \oplus \mathbf{u} = (16.66 \cdot 2.4, 16.66 \cdot 0.3, 16.66 \cdot 0.3) = (40, 5, 5) = \mathbf{B1}$ (Figure 1); $\mathbf{A2} \oplus \mathbf{u} = (33.33 \cdot 2.4, 33.33 \cdot 0.3, 33.33 \cdot 0.3) = (80, 10, 10) = \mathbf{B2}$; and $\mathbf{A3} \oplus \mathbf{u} = (66.66 \cdot 2.4, 66.66 \cdot 0.3, 66.66 \cdot 0.3) = (160, 20, 20) = \mathbf{B3}$. As in the previous case, $\mathbf{B1}$, $\mathbf{B2}$, and $\mathbf{B3}$, compositionally, are scale-invariant and belong to the same compositional class B (Figure 1). Moreover, perturbing vectors are also scale-invariant, since every compositional class of perturbing vectors will translate some homogeneous coordinates of one compositional class to another. Let $\mathbf{u} = [2.4, 0.3, 0.3]$, a perturbing vector, and a a scalar of value 2; $\mathbf{A1} \oplus a\mathbf{u} = [16.66 \cdot 2 \cdot 2.4, 16.66 \cdot 2 \cdot 0.3, 16.66 \cdot 2 \cdot 0.3] = [80, 10, 10] = \mathbf{B2}$, that is, still some homogeneous coordinates of the compositional class B.

Compositional data analysis also encompasses the geometry of the simplex (S^d). In most circumstances of compositional interest, the data are transformed to some relative values by the closure operation (C), which divides every component by the vector total amount, multiplying the result by an arbitrary constant k (a real number) that will be the new total amount of the vector. Let k be equal to 100 and $\mathbf{A1}$ the homogeneous coordinates; their closure will produce the vector $\mathbf{x}$ in the simplex geometry by:

$$\begin{aligned} \mathbf{A1} \in \mathbb{RP}^2 &\rightarrow \mathbf{x} \\ &= [(100 \cdot 16.66)/(16.66 + 16.66 + 16.66), \\ &\quad (100 \cdot 16.66)/(16.66 + 16.66 + 16.66), \\ &\quad (100 \cdot 16.66)/(16.66 + 16.66 + 16.66)] \\ &= [33.33, 33.33, 33.33] \in S^2 \end{aligned}$$

The result is a representation of this compositional class in relative frequencies (in percentages) in the simplex, which is the smallest part of the original Euclidean space $\mathbb{R}^3$ that would contain all possible points expressed as percentages. For a three-dimensional real Euclidean space, it is the two-dimensional triangle whose vertices lie on the value k of the original axes (i.e., the commonly used ternary diagram). In Figure 1, it is the leftmost simplex, but, for example, a second simplex is shown to the right corresponding to a k of 200.

The properties of the simplex are similar to the real projective space and also preclude the use of the operations and properties of the real Euclidean space. There are also significant differences between both geometries. Some of them arise because, in the simplex, after a perturbation, a new closure is again performed to keep the total amount of the perturbed vector as k . Thus, the position of the point can never be interpreted in terms of the real Euclidean space because it depends on the arbitrary constant k . While homogeneous coordinates representing projective points can still be analyzed as vectors in real Euclidean space, if amounts are considered relevant, this cannot be done with vectors of relative values in the simplex. Besides, in the simplex, it is not possible to evaluate translation beyond the perturbation class. For example, let $\mathbf{x}_0 = [50, 25, 25]$, a composition at time 0, and $\mathbf{x}_1 = [60, 20, 20]$ at time 2; the translation from the former to the latter can be explained by the perturbing vector $\mathbf{u} = [1.2, 0.8, 0.8]$, where the first component has increased, and the other two have decreased. But it could also be explained by $\mathbf{u} = [1.5, 1, 1]$, without any change in the second and third components, or by $\mathbf{u} = [1, 0.6667, 0.6667]$, with changes just in those components. Without further information, one cannot decide which perturbing vector participated, beyond the general information on perturbation class.

All chemical data are given as relative vectors in the simplex. We rarely have any information on the absolute amounts. Moreover, chemical data can be expressed in atomic percentages or in mass, both as elements or as oxides. Those different representations that can be modeled as perturbations should provide, in compositional data analysis, the same results, that is, the analysis

should be invariant regardless of how the data have been reported (i.e., perturbation invariant).

Aitchison's (1986) seminal work on compositional data analysis tried to solve the unit-sum constraint in vectors of relative values in the simplex, the spurious correlation and the negative bias of the variance–covariance. Aitchison identified the simplex as the sample space, presented the operations of perturbation and powering (equivalent to the scalar multiplication in real Euclidean space), and developed the variation matrix that completely determines the covariance structure of compositional data. Aitchison proposed two transformations of the $d+1$ -parts vector of relative values in the simplex that should enable the use of common statistical techniques:

- the additive logratio transformation (alr) $\mathbf{x} \in S^d \rightarrow \mathbf{y} = \log(\mathbf{x}_d/\mathbf{x}_{d+1}) \in \mathbb{R}^d$
- the centered logratio transformation (clr) $\mathbf{x} \in S^d \rightarrow \mathbf{z} = \log(\mathbf{x}/g(\mathbf{x})) \in \mathbb{H} \subset \mathbb{R}^{d+1}$

where $\mathbf{x}_d = [x_1, \dots, x_d]$, $g(\mathbf{x})$ is the geometric mean of all $d+1$ components of $\mathbf{x}$, and $\mathbb{H} \subset \mathbb{R}^{d+1}$ is a hyperplane vector subspace of $\mathbb{R}^{d+1}$. Finally, Aitchison demonstrated that this approach was also scale-invariant, permutation-invariant and subcompositionally coherent. The latter is of critical interest because usually not all components are considered (e.g., only a subset of chemical elements is determined).

Compositional data analysis has seen rapid development in recent years, with very significant contributions. In archaeological sciences, Aitchison's work was first echoed by Baxter (1989), and perturbation was used to model changes in compositions due to loss on ignition, tempering and, especially, weathering (see DETERIORATION; Buxeda i Garrigós 1999). A few years later, it was demonstrated that the simplex is a vector space once the inner product, norm and metric of the Euclidean vector space are adapted to the alr or clr transformed data (Pawlowsky-Glahn and Egozcue 2001; Billheimer, Guttorp, and Fagan 2001). Afterwards, working with coordinates with the isometric logratio transformations (ilr) and the sequential binary partitions (or balances) became an essential new development in compositional data analysis (Pawlowsky-Glahn 2003). Such a development solved part of the problems

associated with the alr and clr transformations, by providing coordinates in a real Euclidean vector space (or Hilbert space). These developments provide a mathematically well-founded method that enables application of all common statistical techniques to compositional data, by using variously transformed data (alr, clr or ilr) as appropriate (Martín-Fernández, Buxeda i Garrigós, and Pawlowsky-Glahn 2015). Moreover, comprehensive software packages have been developed to complement the already existing techniques and software when analyzing compositional data (van de Boogaart and Tolosana-Delgado 2013). Thus, the number of different applications is growing fast, and the ongoing development of an algebra and calculus for compositional data announces even more significant and deep changes in the near future (Pawlowsky-Glahn and Buccianti 2011).

SEE ALSO: Mathematics; Statistics in Archaeology

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Computer Applications in Archaeology

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A key transformation in archaeology since the 1950s has been the shift from analog to digital. In 1953, Albert Spaulding was one of the first to highlight the potential use of mechanized and electronic methods of processing archaeological data as a means of handling the variety and quantity of data required for statistical analysis (Spaulding 1953). In 1955, Jean-Claude Gardin and Jean Deshayes implemented an optical coincidence punch card system which captured and sorted observations relating to 4,000 Bronze Age metal tools. Two sets of cards were implemented. In the first set, each card related to a single tool, with a matrix of punched and unpunched holes describing the presence or absence of the different features of that tool. In the second set, each card related to a distinctive feature, and the punched holes indicated which tools exhibited that feature (Gardin 1958). Subsequently, in 1959, Gardin and Peter Ihm implemented what is generally accepted to be the first example of a computer application within archaeology, using it to automatically classify the collection of Bronze Age tools (Cowgill 1967). In the United States, James Deetz is credited with the earliest use of computer-based processing in 1960, performing a cluster analysis of design elements in Arikara ceramics (Cowgill 1967).

These early applications of computers in archaeology display two aspects which have colored approaches through to the present day: issues surrounding the description and classification of archaeological objects, and the use of statistical techniques. These were inextricably linked with a concern for the need to capture the richness and complexity of archaeological data within numerical recording systems in order to facilitate computer-based classification and analysis. Typically, this entailed the definition of

a set of descriptive traits along with predefined values for each state, involving the atomization of data and the selection of characteristics that are seen to be relevant. These numerical codes for the differential states of material objects were then considered amenable to quantitative analysis, employing techniques such as automated sorting, classification, and a range of multivariate numerical methodologies.

The creation of a computer representation or digital model of the data necessarily meant that analysis was predicated upon the entities being capable of representation within the digital model—anything that could not be captured digitally could not be incorporated within the model and subsequently within the analysis. Indeed, the construction of the digital data model was seen to entail a highly reductionist approach in which the complexity of the archaeological data was deconstructed into simpler, more basic entities capable of being modeled. This found resonance in the processual or “new” archaeology of the 1960s, in which a more “scientific” approach was closely associated with hypothesis testing, quantification, statistical techniques, and consequently computer applications. As a result, for much of their history, computer applications in archaeology have been closely associated with formal, “scientific,” rather than processual approaches to archaeology, and computerization frequently came to imply quantification (Doran and Hodson 1975).

This highlights a significant tension that has existed within computer applications in archaeology: their association with quantitative rather than qualitative data. The scientific goals and methodologies commonly linked with computers, requiring precision and algorithmic clarity, did not sit comfortably with the more humanistic approaches related with post-processual or interpretive methods developed by archaeologists in the 1970s and 1980s in response to the “new” archaeology. Consequently, the introduction of new computer applications such as geographic information systems (GIS) in the 1980s was perceived in some quarters as being founded upon old, discredited theoretical positions because of

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their apparent reliance on environmental and other nonqualitative data, coupled with their use of quantitative methods.

Key application areas

The growth in computer power and storage capacity alongside its physical reduction from room-scale to desktop and portable equipment associated with the microcomputer revolution of the 1980s is arguably the most transformational development in terms of computer applications in archaeology, continuing through to the present day with developments in handheld and wearable computers. Increased access to and availability of computer hardware and software meant that most archaeologists, in common with specialists in other disciplines, increasingly turned to computers for their day-to-day work. Word processors, spreadsheets, graphics programs, and databases became embedded in archaeological practice. At the same time, the growth in computer usage in archaeology saw a decline in the emphasis on quantitative methods and an increased focus on the production of texts as part of daily professional practice. In the process, most computer applications in archaeology became reliant on off-the-shelf software: as computers became more pervasive, fewer bespoke archaeological programs were required to meet the demands of the subject. Apart from highly specialized areas such as aerial photograph rectification, geophysical survey, and radiocarbon calibration, most archaeological tasks could be undertaken using widely available commercial packages, and, increasingly in recent years, free open source software. A consequence of this was that by the 1990s, archaeological computing could be seen as essentially in a subordinate relationship with other disciplines such as information science, image processing, computer vision, and geographical science, with little novel development taking place within archaeology beyond the application itself. This might be interpreted as evidence of the maturity and ubiquity of computer applications within archaeology or alternatively as a lack of creativity or ambition.

Other than specialized software for highly restricted archaeological tasks, the main computer

application types include database management systems (DBMS), GIS, and visualization systems, with less commonplace being artificial intelligence/expert systems, simulation systems, agent-based modeling, and the continued use of statistical software. These find application across the discipline in areas such as field survey and prospection, excavation recording, post-excavation analysis, local and regional landscape analysis, and cultural resource management. Beyond details of their specific implementation, debates surrounding these applications generally focus on the structuring of data within the various systems and the analysis and visualization of those data in support of the interpretation of the past.

Recording data

From the outset, the preparation of data for computer applications has entailed a process of abstraction: the identification and selection of the entities of interest which are to be represented within the data structures. For example, early archaeological databases, including many regional sites and monuments inventories, were typically implemented in a simple flat-file structure in which data were recorded in a two-dimensional matrix where each entity was represented by a row (record), and their defined attributes by the columns (fields). Archaeologists subsequently embraced the relational database management system which was capable of modeling the relationships between the different archaeological entities as a series of interlinked flat-file tables, and, in the process, reducing the redundancy common in the single flat-file database and simplifying data retrieval by removing the need to search through multiple identical data fields. For instance, a flat-file system would require as many columns as necessary to record the maximum number of artifacts found within a grave, whether or not it actually had any, whereas in a relational system a single grave record in one table would be linked to its accompanying artifacts (if any) in a second table. The abstraction typically required to structure data took complex entities and simplified them in order to capture them, and in the process focused on certain characteristics while discarding others. Since this has implications for the comparability and reusability

of the data by others at a later stage, attempts were made to enforce standards in the definition and recording of data, either by seeking to impose standard software systems or by requiring the use of standardized terminology through the provision of wordlists or more complex thesauri. Inevitably this was resisted in some quarters as a restriction on practice and placing limits on research, but, if anything, the standardization of terminology has assumed a more significant role as data have moved onto the Internet with the potential to be accessed across national and international boundaries, although in this context these standards are commonly applied to data in a post-hoc manner.

Spatial data

GIS were first used in the United States and only saw wider adoption in Europe later in the mid-1990s. The attraction of GIS was the way in which they could incorporate descriptive data with spatial information and provide an accessible integrated system capable of spatially linking multiple data sources: data tables, digital maps and plans, topographic data, geophysical survey data, georeferenced aerial photographs and satellite imagery, hydrology, soils, and a host of other environmental data, for example. Once incorporated, GIS provided a range of tools capable of performing quite complex analyses on the data in a relatively straightforward manner and characteristically generating visual results. Classically, GIS were employed in different ways in the United States and Europe. In the United States, there was a focus on cultural resource management, including predictive modeling to determine the likelihood of encountering sites. In contrast, in Europe the focus was more specifically linked with landscape modeling within a theoretical context to investigate aspects such as movement, visibility, prominence, and proximity. Although these distinctions have broken down with the passing of time and GIS applications have extended into intra-site and excavation recording systems, it remains the case that predictive modeling for cultural resource management applications has not been widely used in Europe, and where it has been applied in the Netherlands, it has since been criticized for its unreliable results (Kamermans 2007).

In terms of data structuring, a recurring issue with GIS is ironically its spatial determinism: unless an entity can be described in terms of a point, line, polygon, or a set of raster values, it cannot be represented within a GIS data model. This enhanced the perception of GIS as a positivist tool, rooted in processual archaeology, and largely incapable of incorporating cultural and social variables. The resurgence of statistical tests of association and spatial analytical techniques within GIS served to reinforce the view that GIS harked back to an earlier theoretical milieu. Although GIS remains a powerful data management and visualization tool regardless, considerable efforts have been expended in attempts to integrate post-processual landscape analyses employing humanistic, cognitive, and cultural variables within the GIS model. This is frequently achieved through the use of proxies—for instance, visibility standing for perception and knowledge of a place—or through the introduction of new tools and procedures for representing movement and vision, for example, although these are often not available within standard GIS packages.

Visualizing data

Visualization, and especially 3D modeling, has seen a significant growth in use in conjunction with the increased availability of fast computers and powerful software. The earliest examples of “virtual archaeology” were produced using mainframe computers and highly specialized software. The incorporation of tools within computer-aided design (CAD) programs made 3D modeling more accessible, although the architectural and engineering origins of the software tended to mean that reconstruction models were frequently of buildings and often classical in nature. Reconstructions tended to be static views, divorced from their surrounding landscape, and lacking any human dimension. The development of 3D animation software and, more recently, the availability of computer gaming environments and their associated assets facilitated the expansion of archaeological reconstructions into much more ambitious interactive virtual environments, with natural features, textures, vegetation, objects, people, and animals. The increased reliance on computer-generated imagery (CGI) in films and

the immersive qualities of computer games has raised expectations of realism and this has created challenges for archaeological reconstruction. In particular, a focus on realistic representation sits uncomfortably with the levels of archaeological interpretation involved in reconstruction—for example, frequently a structure may consist of no more than foundations so that everything reconstructed above ground is based on interpretation and imagination. It has long been accepted that a computer model carries with it connotations of authority, and the degree of realism achieved is often linked to the perceived level of authenticity represented by the model. Communicating uncertainty and the presence of interpretative elements within the same model while retaining the desire for realism is problematic, and approaches generally rely on accompanying documentation or paradata which describes the decision-making process and the construction pipeline used.

Internet archaeology

In concert with wider society, archaeology has embraced the growth of the Internet, and specifically the World Wide Web, since the mid-1990s, and in many respects this has come to underpin computer applications within archaeology. Although initially focused on the creation of web-sites and indices to websites, increasing access to the Web triggered developments in a number of directions. The reliance of the World Wide Web on hypertext markup language (HTML) encouraged exploration of hypertext, which was seen to provide a means of publication suited to a post-processual view of the past by virtue of its subversion of traditional print text paradigms through its perceived erosion of authorship and empowerment of the reader, and the way it enabled interactivity, multivocality, and reflexivity in its texts. However, reality fell far short of vision: the author has remained paramount and the reader subject to the connections created by the author. Contrary to expectation, text is not being decomposed into chunks and massively interlinked; instead, very conventional whole documents, with much of their structure and paper origins clearly apparent, are loosely linked together. As a result, divisions between author and reader, producer and consumer, have

been technologically reinforced. Indeed, with some exceptions (such as the online journal *Internet Archaeology*) the growth of Web-based archaeological publications is largely reliant on delivering text and images in fixed traditional print layouts, such as provided through the Portable Document Format (PDF).

The Internet has been increasingly employed to provide access to archaeological information to a wider audience. Searchable datasets such as national and local heritage records, providing information about site location, period, and events, and typically provided by national and regional heritage agencies, have transformed approaches to desk-based studies in countries such as the United Kingdom, the Netherlands, and Germany. Downloadable datasets, associated with excavations, surveys, and other archaeological interventions, have also become progressively available in the United Kingdom, the United States, the Netherlands, and Germany, with new digital repositories also being established elsewhere. Coupled with this, considerable attention has been paid to the existence of large bodies of archaeological data captured within traditional published journals and in “gray literature” unpublished reports, and means sought to extract relevant information automatically from their PDFs using natural language processing techniques. At a relatively early stage, this draws upon earlier standards of work and aspects of artificial intelligence in order to construct ontologies: structured syntaxes for describing and capturing the concepts and contexts of information and the relationships between them. These provide a means for establishing interoperability between disparate datasets and constitute the “linked data” which underpins the creation of the Semantic Web. Aligning datasets collected by different people at different times and in different places is challenging, and furthermore sits somewhat awkwardly with a situated and contingent view of archaeological information, but the benefits of linking and sharing data are beginning to be demonstrated through large-scale synthetic analyses which would be difficult if not impossible to achieve in their absence.

Making data available in these ways and facilitating their reuse is seen as a key means of ensuring their survival, and this principle underpins archaeological digital archives such as

those provided by the Archaeology Data Service (UK), tDAR (USA), and Open Context (USA). Most professional codes of ethics require archiving of digital data, but there remains a degree of dislocation between the funding of models of these archives and their role as suppliers of data of record: for the most part, funding is insecure, dependent on grant aid or the generation of commercial income. While it is possible to demonstrate the value of these resources in financial terms, this is primarily associated with the benefits of access to online indices and inventories for commercial desk-based analyses, whereas the value of the reuse of archived primary data has proved harder to demonstrate, despite its perceived importance among the archaeological community. With national governments promoting open access to data, heritage agencies are perhaps in a stronger position to support access to data, but again this largely relates to the provision of management inventories rather than primary datasets.

Computing futures

Predicting the future directions of computer applications in archaeology is unlikely to be successful; however, a number of characteristics can be identified. A continued reliance on applications developed in other fields for different purposes may be anticipated, together with the benefits that might accrue—for example, the recent demonstrations of the value of publicly available satellite imagery in the discovery of new sites and tracking the damage inflicted on known sites within conflict areas. The disparate nature of archaeological data, with its variety, complexity, and spatial and temporal dimensions, will continue to be an attraction for the development of linked data and natural language processing. There is also the way in which tools and techniques which may not initially be transformative can subsequently re-emerge in new areas: for instance, artificial intelligence techniques and expert systems never took off in a significant way in the 1980s, but are integral to developments associated with automated data processing and “big data” analysis. Visualization of archaeological data is clearly an area of future growth, and it might be anticipated that it will

expand in new directions—for instance, linking gaming engines and their environments with agent-based modeling—and there is the imminent challenge of virtual reality and augmented reality. In a field that is constantly changing, one thing is certain: that computer applications in archaeology will develop in exciting and unpredictable ways.

SEE ALSO: Artificial Intelligence; Augmented Reality; Databases in Archaeology; Digital Media in Archaeology; Image-Based 3D Modeling; Information Modeling; Parallel and Distributed Computing; Simulation Modeling; Statistics in Archaeology

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Correspondence Analysis

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Correspondence analysis (CA) is an exploratory statistical technique that allows us to represent graphically the dependence between rows and columns of contingency tables (also called “cross-tabulations”) in order to discover hidden patterns of association and to facilitate data interpretation. While the foundations of this technique are in the work of K. Pearson and R. A. Fisher, namely in their analysis of contingency tables (see HYPOTHESIS TESTING), the origin of CA can be traced back to the French linguist Jean-Paul Benzécri, who in 1960 developed it in its current form and who can therefore be considered its father. CA has been adopted and further developed by scholars elsewhere in Europe and beyond, so that today different schools can be isolated in continental Europe (e.g., Italy), Asia, Australia, and New Zealand. In archaeology, CA has been slow in gaining popularity by comparison to other multivariate techniques, for instance multidimensional scaling, which was used for seriation purposes as early as the 1970s (Kendall 1971). In the early stages of its development, CA had in fact difficulties in reaching non-French-speaking scientific communities because of the gap between Benzécri’s group in France and Anglo-American statistical schools. Interestingly, early uses of CA in archaeology date back to about the same period when CA’s popularity increased beyond Europe—namely the 1980s. The first applications of the technique to address archaeological problems allow us to detect an early interest in it manifested by central European scholars (Bølviken et al. 1985; Madsen 1989).

CA is particularly well suited to archaeology because archaeological data often lend themselves to contingency tables that cross-tabulate levels of a categorical variable against levels of another such variable. As a case in point, let us consider funerary data (see BURIAL EXCAVATION): a typical

table could put in relation a ‘tomb’ variable with an ‘accompanying object’ variable. As a result, tombs would be listed in the table’s rows (each row representing a burial), while accompanying objects would be listed in the columns (each column representing an object type). Individual cells would contain the frequency with which each object occurs in each burial. Besides being a useful means to summarize data, such a contingency table can be thought of as embedding information about the underlying patterns of association (if any) between rows and columns. To keep the same example, the archaeologist’s interest could lie in understanding the relation between burials and accompanying objects, and especially in assessing whether there is any *correspondence* between a particular burial (or group thereof) and a particular accompanying object (or group thereof). By extension, the aim could also be to assess whether groups of burials characterized by the occurrence of specific objects can be located, or whether groups of objects that occur in specific groups of burials can be isolated.

While the existence and the strength of the association between rows and columns could be tested and gauged via Pearson’s chi-squared test of independence and categorical association coefficients (e.g., Pearson’s phi, Cramer’s V) respectively (see CHI-SQUARE ANALYSIS), the aforementioned goals can be meaningfully addressed with the aid of CA. CA reduces the number of dimensions needed to display a table by decomposing data variability (termed *total inertia* in CA terminology) and by defining the smallest number of dimensions capable of capturing it. The graphical output of CA is a scatter plot where row and column profiles (i.e., sets of relative frequencies into which rows and columns are preliminarily turned) are represented as points on a sequence of low-dimensional spaces. These retain a decreasing amount of the total inertia, whereby the first dimension will capture the highest amount, the second will account for the second largest portion, and so on. On the scatter plot, the distance between data points of the same type (i.e., row-to-row; column-to-column) is related to

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the degree to which the rows have similar profiles. The more the points are close to one another, the more similar their profiles are. The origin of the axes can be conceptualized as the place where there is no difference between rows and columns profiles; or, more formally, it represents the hypothesis of homogeneity of the profiles.

One of the crucial aspects of using CA and interpreting its results is the selection of the number of dimensions to be considered useful for data interpretation. In fact any analyst must face a trade-off between the increase in explained data variability that results from keeping many dimensions and a correspondingly increasing interpretational complexity that derives from choosing more than two dimensions. There are different views on how many dimensions to retain; and they range from informal approaches, whereby only those dimensions to which one can give a meaningful interpretation should be kept, to more formal approaches, such as choosing as many dimensions as are necessary to explain a preestablished level of data variability. Yet other methods exist as well. They comprise the use of the so-called scree plot (first employed in the context of principal component analysis (see *PRINCIPAL COMPONENT ANALYSIS*)) as a visual aid to the selection of dimensions; the retention of dimensions that explain more than the average inertia; the use of chi-squared-based methods such as the so-called Malinvaud's test; and the use of a test allowing to repeatedly perform CA in a randomized fashion, in order to derive a distribution of simulated dimensions against which to compare the dimensions that stem from the observed data. The rationale of this last approach is that nontrivial dimensions should explain a larger percentage of inertia than dimensions derived from random data (for a summary of the methods discussed here, see Alberti 2013, with further references). However, regardless of any compelling dimension-retaining reason, it is often advisable to inspect dimensions other than the first two, since interesting patterns of associations can emerge in higher-dimensionality spaces.

Besides the visual inspection of the CA's graphical output, namely the scatter plot of row and/or column profiles on the plane defined by a pair of selected dimensions, other aspects prove crucial if we wish to gain a rich interpretation of the data structure. The first is assessing which

row or column category is actually contributing to the definition of the selected dimensions; this allows us to understand the 'meaning' of the latter. The second relevant aspect is to assess which row or column categories are more correlated to which dimensions. To accomplish both tasks, the analyst is guided by some CA diagnostics that are routinely reported by any modern computer program, such as the contribution of each row or column category to the inertia explained by the individual dimensions, and the list of the squared cosine. Once the square root of the cosine is calculated, it can be interpreted as a correlation coefficient between each row or column category and the individual dimensions. The squared cosines also allow to quantify how well displayed a row or a column category is on the plane defined by the selected dimensions. For any category, adding up the squared cosine indicates what percentage of inertia is captured by the selected CA plane. The position of points characterized by a low quality of the display must be interpreted with caution.

CA may also provide a basis for formally seeking for clusters among rows or columns (see *CLUSTER ANALYSIS*). A method particularly well suited to the logic of CA uses a progressive aggregation of rows (or columns) in such a way that every successive merging produces the smallest change in the table's inertia. This process can be graphically represented by means of a tree-like diagram and goes on until the table boils down to a single row. Methods also exist to decide how many clusters can be read out from the tree: one such method identifies a cutting threshold at the level at which there is a balance between the within-group and the between-group inertia (Husson, Lê, and Pagès 2011). Another approach proposes to perform a Euclidean distance-based hierarchical clustering using the row or column coordinates on a subset of dimensions in which the data points are well displayed (Ciampi, Marcos, and Limas 2005).

Today CA is widely used in archaeology for different purposes, which range from the study of intra-site activity areas, burial assemblages, and the on-site distribution of faunal remains to the distribution of types of drinking pottery in the context of contact between societies, to stratigraphy and formation processes, or to chronological seriation. The favor encountered by CA in this last kind of analysis is due to its very ability

to highlight and disentangle different trends embedded in the data. CA also has the advantage of not searching for seriation; rather, by dissecting trends in the variability of the data, it reveals whether a seriation structure exists in those data. The presence of such a structure is evidenced by the typical horseshoe (i.e., parabolic) shape of the cloud of row and column points on the CA scatter plot. In such instances, rows and columns of the input contingency tables can be sorted according to the coordinates of the corresponding row and column points on the selected dimensions (usually, but not invariably, the first two). The resulting ordering can be conceived of as having a chronological meaning (in terms of the relative chronology between row and column categories), provided that the input data are sensitive only to time and not to other synchronic factors, such as status, gender, or age, in the case of burial data (Kjeld Jensen and Høilund Nielsen 1997).

The increasingly wider use of CA technique in archaeology as well as in the social science in general is favored by the ready availability of software capable to perform CA. Virtually all commercial statistical programs provide this kind of facility. Even more importantly, CA can be performed by means of a number of free software programs that come either as stand-alone ones (e.g., Hammer, Harper, and Ryan's PAST) or as Microsoft Excel add-ins (T. Madsen's CAPCA). CA is also provided by many packages built to be used within the R statistical programming environment, many of them written by leading scholars in the field of CA computation, as for instance Nenadic and Greenacre's CA, Husson and Pagès's FactoMineR, de Leeuw and Mair's anacor, or Beh and Lombardo's CAvariants. Other packages (e.g., CAinterprTools) aim at facilitating the interpretation of CA's results and allow adding some inferential aspects to the analysis. All these programs can be easily found through a web search. Further, many of them provide the facility to perform other types of multivariate analysis besides CA as well as interesting variants and extensions of CA that have not yet found use in archaeology, for example, nonsymmetric CA, or have been less used than simple CA in this field, for example, multiple CA. Nonsymmetric CA is used

to analyze tables with a dependence structure, that is, tables where rows depend on columns (or vice versa), whereas multiple CA allows the analysis of more than two categorical variables.

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Databases in Archaeology

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The storage of archaeological data in, and their retrieval from, digital databases are by now essential components of archaeological research. Relational database technology was introduced in the 1970s as a way to standardize the data recorded in narrative form (Codd 1970) and provided an important enhancement of the archaeologist's repertory of data analysis tools. Software applications that permit the creation and maintenance of relational databases are superior to traditional, paper-based solutions—superior, that is, in terms of storage, ease of access, space saving, and searching; and their continuous improvement over the past 20 years has led to a widespread use of digital databases in archaeology. Given the growing accessibility of statistical techniques and the ease with which they can be applied, databases have made it possible for archaeologists, who work both as researchers and as professionals, to implement complex quantitative analysis when they examine their datasets.

Databases

A database is usually a collection of data organized for rapid search and retrieval by a computer. It is composed of schemas, tables, forms, queries, reports, and other objects. In other words, it is a prescribed storage area in the computer file system, and it is managed by a dedicated software. Usually the software has a graphical user interface (GUI) that permits easy use toward the creation of a database project. A relational database management system (RDBMS) is a digital database based on a series of tables (or relations) of data linked to one another—that is, designed to

interact among themselves for the efficiency of data organization, avoiding repetition of data entry and data error. Each table is a data structure composed of columns and rows; it has a unique (primary) key that identifies each row, describes relationships between sets of attributes (columns) and records (rows), and represents an entity type, such as a stratigraphic unit (context). The rows are instances of that type of entity (e.g., a single stratigraphic unit) and the columns describe values attributed to those instances (e.g., unit number, components, artifacts). In order to create the tables, it is necessary to know the kinds, quantity, and relationships of the data that one needs to manage (strings, numbers, date, etc.). The relationships among tables are logical models of the relationships between the variables defined for each table. These relationships are fundamental for structuring the tables and their links to one another. They are realized through a column that contains the primary key—that is, a unique index for each row that interlinks all the attributes in the table (e.g., an index that could be used in a table recording stratigraphic units is the number of the unit itself). Each number is unique to each stratigraphic unit, so it may be used as an identifier—say, of the pottery present in a context that is described in another table. In order to link tables, it is necessary to use the key number of the stratigraphic unit as a foreign key that links objects to their context; for example, in a ceramics table, the key number of the stratigraphic unit would link the ceramics in question to their respective context. Generally it is possible to link one single record (row) either to one or to many records. A table also has a user-friendly form, which allows easy entry of data and rapid navigation among the forms. The forms may be grouped into two different user interfaces. The first, where the forms show all the fields of the data-archiving tables, specifically addresses data-entry operators (administrators); the second, where the forms mainly provide query results, specifically addresses users who consult the database. A relational database uses the

Structured Query Language (SQL) for querying and maintaining the database. In the last years of the first decade of the twenty-first century, a generation of postrelational databases called NoSQL databases introduced fast key-value stores and document-oriented databases. NoSQL databases are used with big data approach. Currently a new generation known as NewSQL databases experimented new implementations that are able to retain both the relational/SQL model and the NoSQL model, with its high performance (Moniruzzaman and Hossain 2013).

Databases in archaeology

Planning the architecture of an archaeological relational database should represent a significant effort on the total research design. The database design is aimed at minimizing potential errors in the population and at maximizing data analysis, including the possibility for other researchers to reuse the data. In order to create an efficient database, the organizers of archaeological data should adhere to the rules of archaeological documentation management: it must be as comprehensive as possible and must lead to better analysis, publication, and archiving. Considering archaeological practice, it seems obvious that a single or unique industrial approach is not possible: each project database has to be designed on its own, taking into account the overall research design and expectations for data recording, the project's resources, and the team's technological level. This means that a large part of designing revolves around deciding what types of data to preserve, which attributes are valuable for data collection and analysis, and what relationships are created by choosing these significant attributes (and not others). The choice of the attributes to be recorded (e.g., ceramic type, origin, occurrence) has long-term implications for how a dataset may be reused, whereas the definition of the relationships with other archaeological analytical units—such as sites, archaeological intervention, stratigraphic units, artifacts, and so on—is critical to data analysis and to curation. Open-source software (MySQL, PostgreSQL, SQLite, etc.) versus proprietary software (Microsoft Access, FileMaker Pro, etc.),

cross-platform capability, usability, output, and data integration are all aspects to take care of in the overall data collection and preservation. Ease of access through a wide variety of front-end user interfaces, from GIS to web browsers, increases a database's usefulness to archaeological projects. Unfortunately archaeologists have been slow to take complete advantage of relational architecture, although the latter often mirrors the way archaeological data are structured. The purpose of relational database normalization is to limit each table to a single theme, such as ceramics, which can be related through internal indexes to other tables, such as tables of origin. There is no general rule about the degree and granularity of normalization that should be used. The degree to which data are split into single themes depends upon data organization needs. Generally the core of archaeological databases is their origin (site, archaeological intervention, stratigraphic unit, etc.), given the fact that archaeological data are firmly rooted in locations. Indeed, (geo)location, whether it be intra-site or inter-site, permits archaeologists to meet the basic goals of relational comparison, even if the analytical level at which the location is recorded varies widely from project to project. More granular levels of data collection are represented, for example, by artifacts (pottery, lithics, botanical and/or faunal remains, etc.) inside their stratigraphic unit, and by attributes inside artifact sets or classes.

Thesauri

In order to ensure consistency both within a database and across databases, it is necessary to apply some form of data standards. Central to the application of data standards is the construction of thesauri—lists of values that are necessary for filling in certain fields in guided mode and that control the nomenclature (e.g., site, monument types, pottery types). The importance of thesauri lies in the prevention of inaccurate data and in the searching process itself. In the absence of controlled terminology, searches such as the one for types of pottery are unavoidably compromised. Nonstandardized language can lead to inefficiencies that render the collected data completely unusable.

Thesauri can be divided into:

- closed thesauri, with values that cannot be modified by the searcher; these are vocabularies with a very high level of language processing;
- open thesauri, which do not apply restrictive control of language and allow restrictions to be bypassed through automatic updating when the data are entered. These thesauri are usually adopted for columns for which it is not currently possible to establish a univocal set of values. These vocabularies tend to turn into closed lists gradually, as the reliability of the sample increases. Open thesauri can also be used for data that, given their nature, cannot easily be used in closed lists, for example, fields containing the names of the principal investigator or of the individuals performing the investigation.

Thesauri may be used on their own or organized hierarchically along levels to form an ontology; a good example of the latter is the *Art & Architecture Thesaurus* (<http://www.getty.edu/research/tools/vocabularies/aat>) at the Getty Research Institute.

Chronology

In this context, chronological data management is a key factor in allowing information interoperability. Information is often heterogeneous and dissimilar in terms of chronological definition. Sometimes the data collected also present a certain margin of uncertainty owing to specific contexts or, more generally, to the status of the research. A simple system for managing this information is based on a chronological interval defined by two different number fields called “final chronology” and “initial chronology,” in which the absolute date is included. Centuries can be dated by starting at year 1 and ending at year 100 (the subsequent year). Data can be retrieved thanks to a query—which is conducted on both numerical data in order for an interval to get defined. Number scanning can be accompanied by a chronological thesaurus expressed in text form, which allows for simplified searching:

macroperiods can be divided into subperiods, and so on.

Mobile devices

Mobile devices are the newest and most exciting tools in the archaeologist’s kit. Technologies such as voice data entry, skip logic on touch screens, and wireless networks have opened access to databases and represent a great promise for those who have to enter coded data for large datasets. Thanks to the introduction of tablets (iPad- and Android-based) from 2010 on, archaeologists finally have a device that works all day, is connected to the network even if it does not need it, and has a screen wide enough to allow direct digital entry during fieldwork. In this way the native digital workflow replaces the traditional workflow on paper and opens immediate access to data search and retrieval and to their review. Above all, databases on mobile devices encourage rethinking the best practices for recording and interpreting the past and lead to datafication, which is the act of transforming objects and processes by giving them a quantified format, so they can be tabulated and analyzed. Datafication promises to go beyond digitization and to have an even more profound impact on archaeology, challenging the foundations of our established methods of measurement and providing new opportunities. Indeed, datafication fits a big data approach and permits more sophisticated mathematical analyses dedicated to identifying nonlinear relationships among the data. In other words, to datafy archaeology would mean to produce a flow of data starting from those produced through the archaeological practice, for instance locations, interactions, and relations between finds and sites (Gattiglia 2015).

Because the data management scheme is tailored to the research design, the use of mobile devices to create digital-born data is a decision that each project should make for itself. The PARP:PS project, for instance, experimented with databases running on the iPhone in 2009, and in 2010–12 started using iPads to enter and edit records in the database, draw scaled plans and profiles, keep a free-form notebook, and keep Harris matrices up to date. As a result, the

PARP:PS project has a full native digital archive (Wallrodt 2016, 44).

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Descriptive Statistics

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Introduction

The basic principles of statistics help us to determine what conclusions are reliable and, more generally, provide the navigational guidance for making advances in science and addressing societal issues. Two basic divisions of statistics are inferential statistics and descriptive statistics. While descriptive statistics is concerned with the expression of data, inferential statistics deal with the conclusions drawn from the data/details. Thus, the available information with which we are concerned is called data, and is usually in the form of numbers. The concepts and methods necessary for achieving the objective of summarization are presented in terms of numerical facts, or data, in either tables or graphical form, and with the methodology of analyzing the data. Irrespective of the area of research, descriptive statistics forms an integral part of analysis and presentation of any set of observations. Here we have chosen data simple enough to gain an overview and a better understanding of the topic. Various statistical methods/techniques specifically concerning the various issues in archaeology have been described in the literature (Drennan 2009; Baxter 2010) and cover plenty of archaeological cases.

Some of the necessary words and phrases for an understanding of statistics are listed here:

Population: A population is the universal group from which data are sampled.

Sample: A sample is a part of a population provided it represents the whole population.

Variable: A variable is a feature characteristic of any member of a population differing in quality or quantity from one member to another.

Quantitative variable: A variable differing in quantity is called a quantitative variable, for example, age, height, weight of a person, and so on.

Qualitative variable: A variable differing in quality is called a qualitative variable or attribute, for example, eye color, gender, religion, and so on.

Discrete variable: A discrete variable is the one that can take only certain isolated values, for example, number of members in a family, number of errors in a book, and so on.

Continuous variable: A continuous variable is one which can take all values within certain specified range, for example, age between 20 to 70 years.

Measurement scales: This may be defined as the assignment of numbers to objects or events according to a fixed set of rules. It is important to understand the role of various scales used in statistics. Here is a brief summary of these scales.

- *Nominal scale:* It is categorical in nature and there is no preference for one category over the other. Nominal data has no ordering and it is not metric, for example, gender, religion, and so on.
- *Ordinal scale:* It is also categorical in nature but in this scale order is important. For example, severity of disease (mild, moderate, severe), or socioeconomic class (lower, middle, upper).
- *Interval scale:* On an interval scale, mathematical operations may not be valid. Plus or minus may be valid, but not multiplication and division. It is metric in nature. Moreover, zero has a meaning, for example, temperature, beauty scores, and so on.
- *Ratio scale:* In ratio scale, all mathematical operations (+, −, ×, /) are valid. It is also metric in nature, for example, height or weight. Nominal and ordinal scales are used for categorical data, and interval and

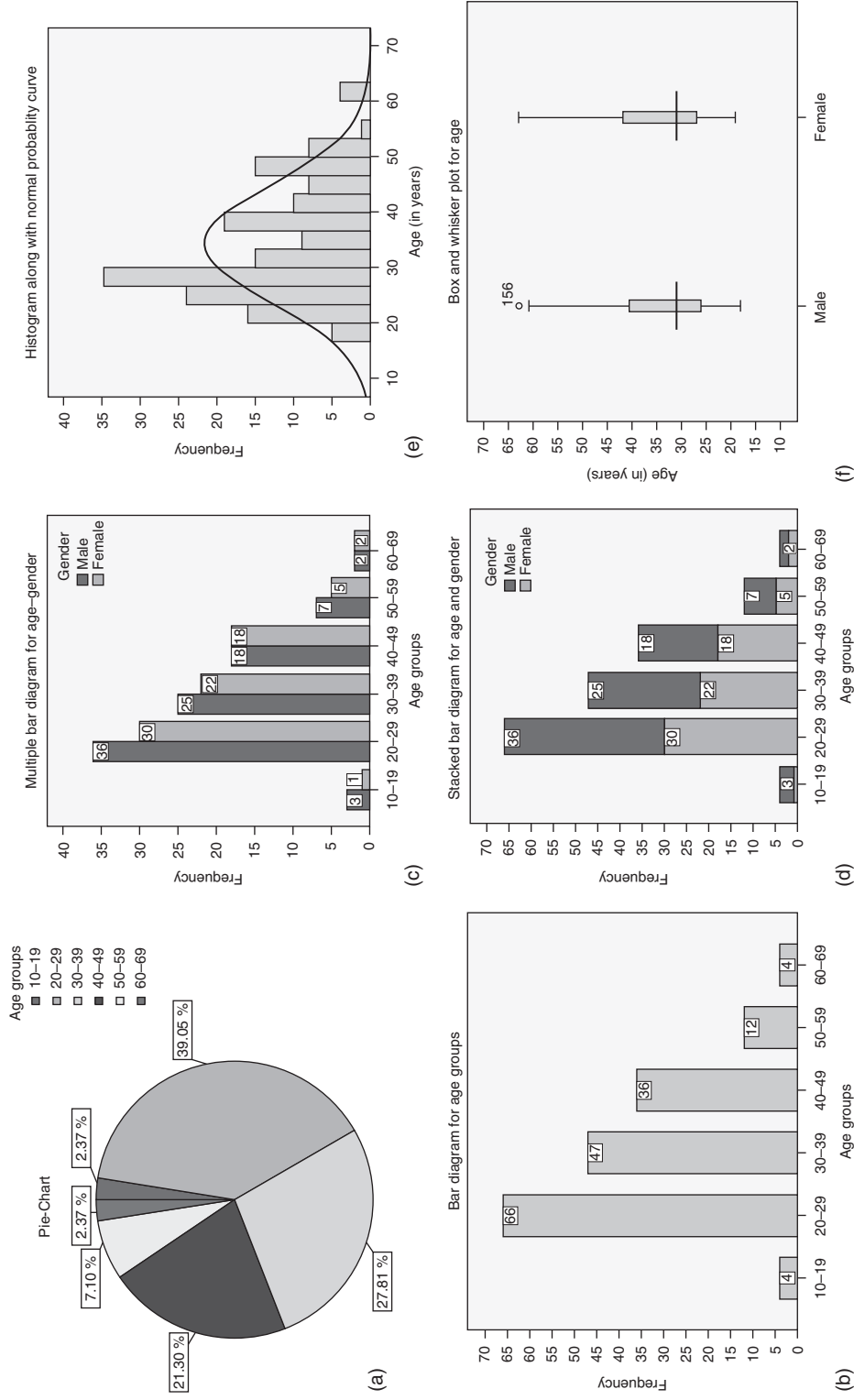


Figure 1 (a) Pie chart. (b) Simple bar chart. (c) Multiple bar chart. (d) Stacked bar chart. (e) Histogram with normal probability curve. (f) Box and whisker plot. The graphical representations shown in (a) to (e) are for the data shown in Table 1.

Table 1 Age and gender distributions of 169 patients (sex code: 1 = male, 2 = female).

Age	Sex	Age	Sex	Age	Sex	Age	Sex	Age	Sex	Age	Sex	Age	Sex
18	1	33	1	23	2	37	1	25	1	41	2	27	2
22	2	37	2	24	1	40	1	27	2	45	1	28	1
24	2	40	1	26	1	44	1	28	2	48	1	30	2
26	1	43	1	28	1	48	2	30	2	53	2	32	1
27	1	47	2	29	2	53	2	31	2	22	1	35	2
29	1	51	2	31	1	21	1	34	1	24	1	38	1
30	2	19	2	33	1	23	2	38	2	26	2	42	1
32	2	23	2	37	2	25	1	41	2	27	1	46	1
37	1	24	1	40	1	26	2	45	1	28	1	49	2
40	2	26	1	44	1	28	1	48	1	30	2	61	1
43	1	27	2	48	2	30	1	53	1	31	2	22	1
47	2	29	2	52	1	31	1	21	2	34	2	24	2
51	1	31	1	20	1	34	2	23	2	38	2	26	1
18	1	33	1	23	2	38	1	25	1	41	1	27	1
23	1	37	1	25	2	40	1	27	2	45	2	29	2
24	2	40	2	26	2	44	2	28	1	49	2	30	1
26	1	43	2	28	2	48	1	30	2	56	1	32	1
27	1	48	1	29	1	53	1	31	1	22	1	36	2
29	2	52	2	31	2	21	2	34	1	24	1	39	2
30	1	19	1	34	2	23	1	38	1	26	2	42	2
46	2	24	1	30	2	42	2	22	2	29	1	39	1
50	1	26	1	32	1	47	1	24	1	30	1	42	2
62	2	27	1	36	2	50	1	26	1	32	2	47	2
22	2	29	2	39	1	63	1	27	2	36	1	50	2
63	2												

ratio for measurement data (Johnson and Bhattacharyya 2014). Of course, with some expertise, conversions are also possible.

Primary and secondary data: When data is used for the purpose for which it was originally collected, it is known as primary data; when it is used for any other purpose subsequently, it is termed secondary data. For example, if a company buyer obtains quotations for the price, delivery date and performance of a new piece of equipment from a number of suppliers with a view to purchase, then the data as used by the buyer is primary data. Should this data later be used by the Budgetary Control department to estimate price increases of machinery over the past year, then the data is secondary.

Graphical representation of data: A graph is a method of presenting statistical data in visual form. A well-designed graphical presentation can effectively communicate the data's

message in a language readily understood by almost everyone. The graphical methods for describing data are intuitively appealing. They can be used to describe either a sample or a population, and quantitative or qualitative datasets. The different possible methods of graphical representation of data are described below based on a dataset shown in Table 1.

- *Pie chart:* Pie charts are widely used to show the component parts of a total. They are popular because of their simplicity. In constructing a pie chart, the angles of a slice from the center must be in proportion with the percentage of the total (Figure 1a).
- *Simple bar chart:* The horizontal bar chart is also a simple and popular chart. Like the pie chart, the simple vertical bar chart is a one-scale chart. In constructing a bar chart, it is noted that the width of the bar is not important, but the height of the bar must

be proportional to the frequency of that category (Figure 1b).

- *Multiple bar chart*: A multiple bar chart is particularly useful if one desires to make a quick comparison between different sets of data (Figure 1c).
- *Stacked bar diagram*: A component bar chart subdivides the bars in different sections. It is useful when the total of the components is of interest (Figure 1d).
- *Other type of graphs*: Graphical presentations can be made more attractive through the use of careful layout and appropriate symbols. Sometimes information pertaining to different geographical areas can even be presented through the use of a so-called statistical map. A pictograph diagram illustrates statistical data by means of a pictorial symbol. It can add greatly to the interest of what might otherwise be a dull subject. The chosen symbol must have a close association with the subject matter, so that the reader can comprehend the subject under discussion at a glance.

Frequency distributions

Statistical data obtained by means of census, sample surveys or experiments usually consist of raw, unorganized sets of numerical values. Before these data can be used as a basis for inferences about the phenomenon under investigation or as a basis for decision, they must be summarized and the pertinent information must be extracted.

A useful method for summarizing a set of data is the construction of a frequency table, or a frequency distribution; that is, we divide the overall range of values into a number of classes and count the number of observations that fall into each of these classes or intervals. The general rules for constructing a frequency distribution are:

1. There should not be too few or too many classes, generally between 5 to 15.
2. As far as possible, equal class intervals are preferred. But the first and last classes can be open-ended to cater for extreme values.

3. Each class should have a class mark to represent the classes. It is also named as the class midpoint of the i th class. It can be found by taking a simple average of the class boundaries or the class limits of the same class.

These steps may be followed to make a frequency distribution table (Nick 2007): suppose we have a sample of n observations that we want to group. First compute the range (R), that is, the difference between highest (H) and lowest (L) value, say $R = H - L$ (see below). Then the number of classes (k) is computed, using Sturge's formula; $k = 1 + 3.322 \log_{10}(n)$, and then the class interval width (w) is given by $w = R/k$. There are other rules of thumb that are useful in setting up class intervals. Sometimes, a class interval of 5 units or 10 units, and widths that are multiples of 10, tend to make the summarization more comprehensible. However, the rule of thumb is very subjective.

Relative frequency

Often, it is important to know the proportions of observations, rather than the number of observations, falling in a particular class interval. This information can be obtained by dividing the number of values in a particular class interval by the total number of values. For example, if out of the total of 200 values, 40 values fall in the class interval of say 30 to 40, the relative frequency will be $40/200 = 0.20$. Multiplying this by 100, we can say that 20 percent of values fall in this class interval. The proportion of the values falling within a class interval is referred to as the relative frequency of occurrence of values in that interval. This is illustrated in Table 2 and Figure 1e.

Measures of central tendency

In many instances, we need to summarize the data by means of a single number, called a descriptive measure. These measures can be computed for a sample or for a population. If they are computed for a population, then they are known as parameters, while those computed for samples are called statistics. Commonly used measures

Table 2 Frequency distribution of the ages of 169 subjects (male = 91; female = 78).

Age group	Frequency	Relative frequency	Percentage	Cumulative percentage
10–19	4	0.023669	2.4	2.4
20–29	66	0.390533	39.1	41.4
30–39	47	0.278107	27.8	69.2
40–49	36	0.213018	21.3	90.5
50–59	12	0.071006	7.1	97.6
60–69	4	0.023669	2.4	100.0
Total	169	1.0	100.0	

of central tendency are the *mean*, *median* and *mode*. These measures tell how well a typical value represents the large list of values in the dataset. It is useful for summarizing data and defines the center or middle of the data.

Arithmetic mean or average: The mean is obtained by adding all the values in a sample or population and dividing by the total number of observations. It is denoted by $\bar{x}$:

$$\begin{aligned}\text{Mean} = \bar{x} &= \frac{\text{Sum of all observations}}{\text{Total number of observations}} \\ &= \frac{\sum_{i=1}^n x_i}{n}\end{aligned}$$

The mean is a natural and most widely used measure of location, but it is oversensitive to extreme values. In the case of missing or extreme values, the mean is not the appropriate measure of central tendency as it carries the effect of inflation.

Median: After arranging the data either in ascending or descending order of magnitude, the *median* is the middle-most value which divides the finite set of values into two equal parts. If the number of observations (n) is odd, the median lies in the center, and for an even number of observations, it is the average of two middle observations. It is not really affected by extreme values. Sometimes the median is also referred to as the positional average. It can be computed even with missing data, and can be located graphically also.

Mode: The most frequently occurring value among all observations is called the *mode*. For

example, if a set of values is 1, 5, 4, 5, 5, 5, 7, 3, 5, 2, then the mode is 5. The mode also makes sense for qualitative and categorical data, but the mean and median do not. It does not exist if each observation occurs exactly once. If some observations are repeated an equal number of times, some distributions may have more than one mode. A unimodal distribution has one *mode*, a bimodal distribution two modes, and so on.

Measures of dispersion or variability

Dispersion means scatteredness. We study dispersion to have an idea about variability present in a dataset. If all the values are the same, there will be no dispersion. The amount of dispersion may be small, when the observations are close to each other, but it could be large, if they are widely scattered. For example, consider two series with the following observations:

Series I: 1, 5, 9, 13, 17 (sum = 45, $n = 5$, $\bar{x} = 9$)

Series II: 7, 8, 9, 10, 11 (sum = 45, $n = 5$, $\bar{x} = 9$).

Both the series have five observations and have the same mean of 9. Given the information that the mean of the five observations is 9, we can hypothesize whether it represents Series I data or Series II data; but both means are the same. Therefore, mean alone cannot describe the data completely—the missing part is dispersion. The range of Series I varies from 1 to 17 ($R = 16$), and that of Series II from 7 to 11 ($R = 4$). Thus, Series I is more dispersed than Series II or we can

say that Series II is more consistent than Series I. Commonly used measures of dispersion are *range* and *variance* (or *standard deviation*). The square root of variance is the standard deviation.

Range: The difference between the highest and lowest values is called the range, $R = H - L$. The usefulness of range is limited as it depends only on two observations and not on the entire dataset. These values may carry an inflation effect. The main advantage in using the range is the simplicity of its computation.

Variance: This is the most preferred measure of dispersion. It is based on the notion that when the values of a set of observations lie close to their mean, the dispersion will be less, and if they are far away from the mean, dispersion will be greater. In computing the variance, we subtract the mean from each observation, square the resulting differences, and add up the squared differences. This sum is then divided by the sample size minus 1, to obtain the sample variance, and by the sample size (n), for

population variance.

$$\text{Variance} = \sigma^2 = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2$$

$$\text{Standard deviation} = \sigma = \sqrt{\frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^2}$$

The variance represents squared units and it is not an appropriate measure of dispersion when we wish to express this concept in terms of the original units, and therefore standard deviation is preferred as a measure of dispersion in original units.

Coefficient of variation: When we want to compare the two or more given series in terms of standard deviation or variance, it may lead to fallacious results as they are measured in different units. In such situations, we use *coefficient of variation (CV)*, which express the standard deviation as a percentage of mean. The formula is given by:

$$CV = \frac{\sigma}{\bar{x}} \times 100$$

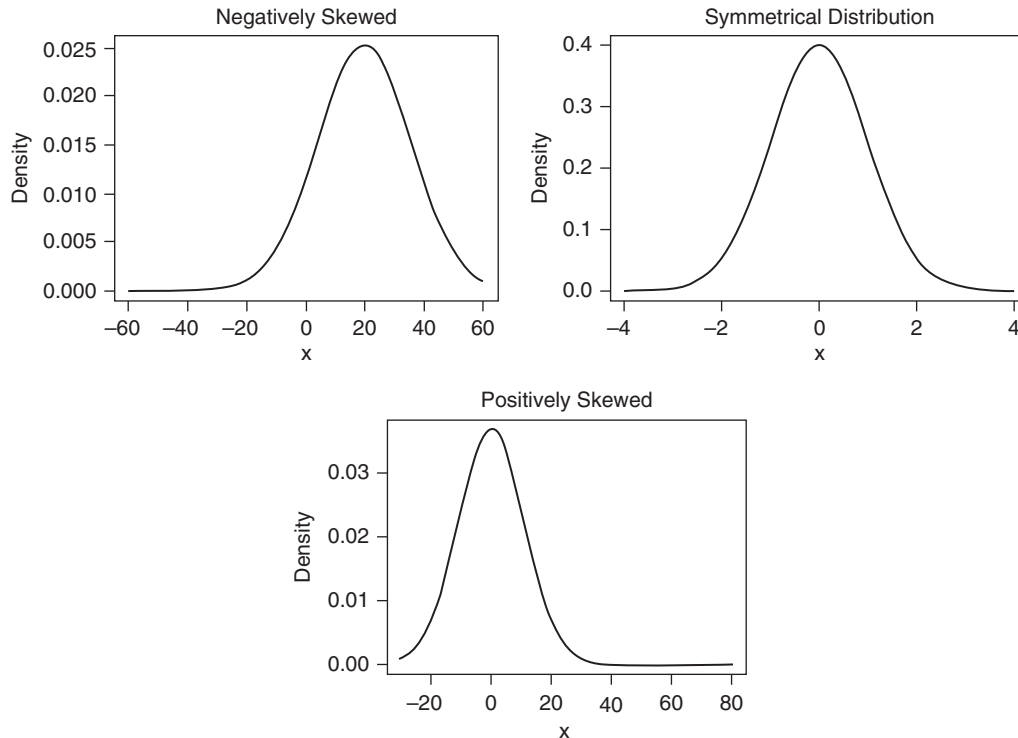


Figure 2 Distributions for negatively skewed, symmetrical, and positively skewed data.

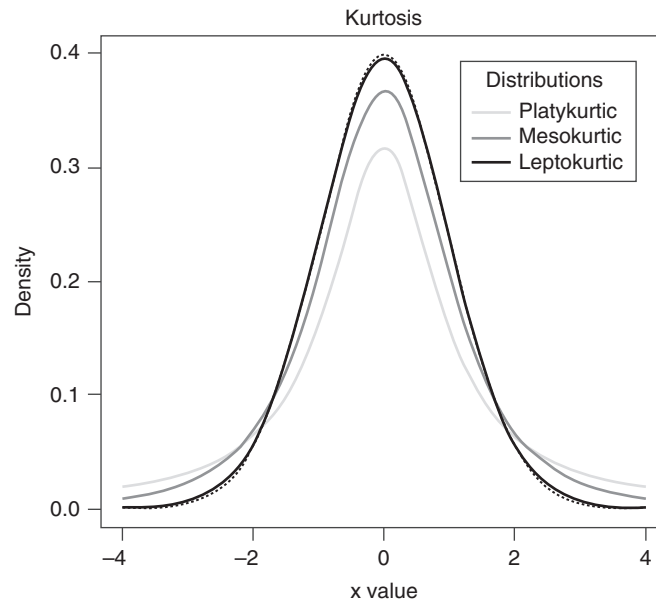


Figure 3 Kurtosis.

Since the mean and standard deviation are measured in the same units, they cancel out in computing the *coefficient of variation*. For sample observations, we replace σ by s (the sample standard deviation).

Partitioning values (percentiles and quartiles): The mean and median are special cases of a family of parameters known as location parameters, so-called because they can be used to designate certain positions on the horizontal axis when the distribution of a variable is graphed. For example, a distribution with a median of 150 is located to the right of a distribution with a median of 100 when the two distributions are graphed. Other location parameters include percentiles and quartiles. We may define a percentile as follows: given a set of n observations, the p th percentile P is the value of a variable such that the proportion p of observations is less than or equal to P and the proportion $(1 - p)$ of the observations is greater than P . Subscripts on P serve to distinguish one percentile from another. The 10th percentile, for example, is designated by P_{10} and the 70th by P_{70} . The 50th percentile, P_{50} , is the median. The 25th percentile is often referred to as the first quartile and it is denoted Q_1 . The 50th percentile (the median) is referred to as the second

quartile Q_2 . Similarly, the 75th percentile is referred to as the third quartile Q_3 .

Interquartile range: A disadvantage of the range is the fact that it is computed from only two values, the largest and the smallest. A similar measure that reflects the variability among the middle 50 percent of the observations in a dataset is the interquartile range. The interquartile range (IQR) is the difference between the third and first quartiles: that is, $IQR = Q_3 - Q_1$.

Box and whisker plot: This is a very useful communicating device containing information about data. A box is drawn between Q_1 and Q_3 , the lower end of the box placed at Q_1 and the upper end at Q_3 . The box is then divided into two parts by a horizontal line that aligns with the *median*. It is generally drawn for comparison purposes. The box and whisker plot drawn for the ages of 169 participants is shown in Figure 1f. The importance of the box plot lies in the fact that it can identify outliers. An outlier is an observation that lies away from the main body of the data. The box plot identifies two types of outliers: probable (marked as 'o') and extreme outliers (marked as '*'). For example, there is one probable outlier among males in Figure 1f.

Moments (definition): The r th-order central moment of a variable x is defined as:

$$m_r = \frac{1}{n} \sum_{i=1}^n (x_i - \bar{x})^r, \quad r = 0, 1, 2, \dots$$

Note that $m_0 = 1$, $m_1 = 0$ always, and m_2 corresponds to the second-order moment, which is equal to σ^2 , the variance, as defined earlier. m_3 and m_4 are called the 3rd- and 4th-order moments. These moments are helpful to determine skewness and kurtosis.

Skewness: This means “lack of symmetry”. We study skewness to have an idea about the shape of the curve that we can draw with the help of given data. A distribution is skewed if:

- 1 Mean $\neq$ median $\neq$ mode.
- 2 Quartiles Q_1 and Q_3 are not equidistant from the median (see box plot).
- 3 The curve drawn with the help of given data is not symmetrical, but stretched more to one side than to the other.

The figures given below show distributions for negatively skewed, symmetrical and positively skewed data (Figure 2). Skewness can be measured either using absolute measures or relative measures, but the best measure of skewness is based upon moment given below:

$$\text{Skewness} = \beta_1 = \frac{m_3}{m_2^{3/2}}$$

where m_3 and m_2 are third- and second-order moments, computed from the given data. If $\beta_1 > 0$, the distribution is positively skewed; if $\beta_1 = 0$, the distribution is symmetrical; and if $\beta_1 < 0$, the distribution is negatively skewed.

Kurtosis: This is a measure of peakedness of the curve. Even if we have measures of central tendency, dispersion and skewness, still we cannot form a complete idea about the distribution, as shown in Figure 3. Kurtosis is measured by coefficient β_2 or its derivation γ_2 given by:

$$\text{Kurtosis} = \beta_2 = \frac{m_4}{m_2^2}, \quad \text{or} \quad \gamma_2 = \beta_2 - 3$$

For a normal curve (also called a *mesokurtic curve*), $\beta_2 = 3$ or $\gamma_2 = 0$. A curve which is flatter than the normal is called *platykurtic*, and for this curve, $\beta_2 < 3$ or $\gamma_2 < 0$. Similarly, the curve that has a higher peak than the normal is called *leptokurtic*, and for this curve $\beta_2 > 3$ or $\gamma_2 > 0$.

SEE ALSO: Analysis of Variance and Covariance; Archaeological Fieldwork; Archaeological Record; Nonparametric Statistics; Statistics in Archaeology

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Digital Heritage

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We are all products of our own society by the very result of being born into a family and a community. We may not even be aware that the heritage that surrounds us is ours—it is simply there—it is intrinsic to our sense of self, and is the anchor that sustains and centers us (Bourdieu 1999). Stepping out of our own comfort zone can be exciting, but acknowledging and respecting another's heritage is how society maintains its integrity and social cohesion. We are witness to vast quantities of new objects entering this cultural ecosystem on a daily, if not hourly rate. Artworks and unique, handmade objects are continually being created and circulated, entering the marketplace to be purchased, collected, and exhibited in the public domain for our appreciation and pleasure. At the same time archaeological excavations are revealing vast quantities of new objects, and with them come their compelling narratives from distant times (see TIME AND TEMPORALITY).

According to The New Renaissance, *Report of the Comité des Sages*,

... new information technologies have created unbelievable opportunities to make this common heritage more accessible for all. Culture is following the digital path and 'memory institutions' are adapting the way in which they communicate with their public (2011, 8).

We are currently witnessing an exponential growth of heritage resources traveling through the digital ecosphere and reaching us from beyond the traditional restraints of space or time. This explosion of digital cultural assets may be seen as a perplexing cacophony, but once organized into intuitive datasets, and made machine readable, they may serve to enrich our

lives when conveyed to us wherever we may be—even directly into the palm of our hand. The challenge we are now facing is how to be able to describe, collect, collate, and disseminate all these archaeological treasures as digital objects, and to be able to wrap them and deliver them together with their descriptions and histories. From the moment that objects are discovered in an excavation and identified, collated, and documented, they are put into systematic order to facilitate analysis, research, and inevitable enchantment by those lucky enough to encounter them. Digital, cultural heritage, once encapsulated with the details of their provenance (metadata), can then be released back into the cultural ecosystem as meaningful narratives and serve to inculcate our sense of self and community.

The veritable explosion of digital possibilities now available to all is almost bewildering, while at the same time the thirst for heritage for individuals and society is almost unquenchable. The insatiable snapping of "selfies" attests to this almost obsessive need to document ourselves, but people also desire to see themselves as fully wrapped in a cultural mantle. There is no better way to understand who we are than by connecting to our histories, and to the structured narratives that move through electronic networks. We can then begin to appreciate our heritage once it is rendered as a comprehensive mapping of society over time and space. There is no single heritage or archaeological sector that remains unaffected by the incredible leaps and bounds of digital possibility. Archaeologists have been documenting objects in the field as they digitize their discoveries in situ. From dig to smartphone, the route is almost a straight line. At the same time, the creative industries are fully engaged in creating platforms and tools to enable the celebration of cultural assets, once the exclusive prerogative of the galleries, libraries, archives, and museums community (GLAM), but now reaching us over websites, portals, mobile apps, and social networks. The results are more than remarkable.

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Still underdeveloped at this time is the systematic linking of heritage within open systems, though digital enterprise. Linked open data (LOD) as a method of linking machine readable assets is still in its infancy, as are solutions developing specifications and standards to support the use of knowledge organization systems (KOS), such as thesauri, classification schemes, and taxonomies within the framework of the Semantic Web. Methodologies such as the Simple Knowledge Organization System (SKOS) are still evolving. This kind of open and systematic linking of assets will serve to open up, and provide direct access to, heritage for everyone—all available in your own language, to be treasured, and savored at your own pace, wherever you are.

The following sections will discuss the circulation of objects in the digital ecosphere of cultural heritage, from the top-down management of cultural heritage to the GLAM community's custodianship of heritage collections and their digital management and telemanagement of archaeology—the evolving visualization platforms that enable the sharing of heritage in the public sphere such as augmented (see AUGMENTED REALITY) and virtual reality (see VIRTUAL REALITY MODELING).

Top-down management of cultural heritage

The term “culture” can be interpreted in different ways and may be mobilized for different agendas. Drawing on the United Nations Educational, Scientific and Cultural Organization (UNESCO) treaty and the Convention Concerning the Protection of the World Cultural and Natural Heritage (see HERITAGE AND POLICY), The World Heritage Convention, adopted by UNESCO in 1972, describes heritage as “... our legacy from the past, what we live with today, and what we pass on to future generations. Our cultural and natural heritage are both irreplaceable sources of life and inspiration.”

According to UNESCO, cultural heritage has the power to transform societies and enrich our lives in countless ways, reminds us how heritage constitutes the core of our identity,

and lays the foundations for vibrant, innovative, and prosperous knowledge societies. Inspired by this directive, the legacy of unique, and often irreplaceable, tangible objects is handed down from past generations to GLAMs, who then assume the stewardship of the cultural and natural heritage on behalf of society. With this responsibility comes the obligation to collect, conserve, and make collections accessible to the public as exhibitions in the present, and to preserve them for the benefit of future generations. In addition to the physical objects circulating in the cultural realm, UNESCO recognizes tangible heritage as encompassing buildings and historic places, monuments, artifacts, and so forth, that are considered worthy of preservation for the future. These include objects significant to the archaeology, architecture, science, or technology of a specific society. In 1994, the World Heritage Committee launched the Global Strategy for a Representative, Balanced, and Credible World Heritage List (see WORLD HERITAGE SITES DESIGNATION) to recognize sites that are of outstanding universal value and meet at least one of ten criteria, selected on the basis of six cultural and four natural criteria.

Heritage is not only about physical objects, however. It also embraces traditions and creativity inherited from our ancestors in an awareness, aware that they are to be valued and passed on to our descendants (see COMMUNITY HERITAGE). Intangible heritage includes, according to UNESCO principles, oral traditions, performing arts, social practices, rituals, festive events, knowledge and practices concerning nature and the universe, and the knowledge and skills to produce traditional crafts. Thus, the tangible and intangible come together to weave the warp and weft of our communities, and the very fabric of our society.

Galleries, libraries, archives and museums (GLAM) community's custodianship of collections

Managing heritage as objects means accessioning them into institutional collections, but as soon as they cross the threshold of past and present they automatically become fossilized

in the historical past. This represents a heterotopian space; a cultural entity that is locked outside of the temporal pace of daily life; a place where the temporal discontinuities cause time to stand still and objects to become fixed in a frozen moment. Foucault (1994, 182) draws attention to the mausoleum-like nature of the modern museum when he describes museums as connected to these temporal discontinuities; as heterochronias—“in which time never ceases to pile up and perch on its own summit.” While heterotopias may be seen as non-places (Augé 1995), as physical spaces that have been geographically misplaced, Foucault recognizes how museums (and libraries) act as heterochronias, and a phenomenon to which he refers as symptomatic of modernity. This resolutely immutable collection of all things that Foucault describes brings to mind a dull and dusty place, where the objects have been so abstracted from daily life that they represent the dead rather than the living. For a museum to be meaningful to living people, the mere preservation and conservation of the historical past is not enough. The act of collecting must be combined with processes of production and interpretation that reunite objects with their provenance and wrap them up into their cultural essentiality. Social anthropologist Alfred Gell (1992) celebrates the wondrous nature of these kinds of objects when he describes the way that anthropological artifacts come into being. He suggests that these objects are the result of a process that emphasizes the technical miracle that must be distinguished from a merely mysterious process. “It is miraculous,” according to Gell, “because it is achieved both by human agency but at the same time by an agency which transcends the normal sense of self-possession of the spectator.” This technical miracle evokes a profound sense of awe in the beholder, a potent intuitive response that Gell identifies as the “halo-effect.” This is the visceral response to wondrous objects that stop you in your tracks when you encounter them on display under an almost hypnotic spotlight and an elevated pedestal.

How to encapsulate these halo-effects, and at the same time release these precious objects from their dusty corners and propel them into the ether of the Internet, is one of the challenges facing the GLAM community today. Objects lose

their spotlight magic once the electricity is turned off in the gallery, and they are diminished further as they are photographed as mere shadows of themselves as digital images, so tiny that they fit snugly into your smartphone—doing little to replenish their lost luster. This is further abstracted by viewing them in a browser, or app, reducing their essence even more as they leave the relative safety of their institutional provenance. The disparity between the real and the virtual is often cause for concern—where these digital specters, depleted of their cultural essence, jostle with other digital entities online to become viral over social networks. As early as 1995 Sherry Turkle addressed the ways that people interact with computers, and the consequences of that interaction. We are still somewhat wary of peering at our screens, while at the same time passionately seeking the information, images, and narratives that we all crave so much. One of the ways to resolve this dichotomy is not to think about the real and virtual as diametric opposites. Pierre Lévy takes exception to the ideas of real and virtual as dialectical counterparts, and argues that

“virtualization, or the transition to a problematic, in no way implies a disappearance in illusion or dematerialization. Rather it should be understood as a form of ‘desubstantiation’ [...] the body as flame, the text as flux” (Lévy 1998, 169).

With an emphasis on heritage and archaeological assets, the following section will consider the management of heritage collections, not as truncated objects that have lost their stories, nor as stories that have become dislocated from their source, but as vibrant entities whose whole consists of a number of parts: the physical and digital, the tangible and intangible, the image and the narrative.

Managing the digital collection and telearchaeology

There are many novel terms describing the management of archaeological assets: teleimmersive archaeology, cyberarchaeology, telearchaeology,

digital archaeology, all aiming to release archaeological, historical, artifacts dug from the depths of the excavation to be transformed into archival data; to move seamlessly from the field and be shared by scholars on the Web (see *COMPUTER APPLICATIONS IN ARCHAEOLOGY*). There is now an understanding that the popular program FileMaker, the database system (see *DATABASES IN ARCHAEOLOGY*) that is used by many archaeological teams, is but part of the chain of events needed to create paperless archaeology. The key to success is the understanding that all data are born digital at the locus level, where spatial data, 3D models, photogrammetry, excavation records, and images are all collated in the field, and processed on the fly to generate and document a total paperless excavation. An example of this kind of holistic approach can be seen in the Jezreel Valley Regional Project (JVRP). The JVRP is a long-term, multidisciplinary survey and excavation project investigating the history of human activity in the Jezreel Valley in Israel from the Paleolithic through the Ottoman period. The interface design for JVRP was built for a field methodology and registration workflow that included synchronization with total station measurements and self-generated context summaries. Major database development was a necessity during the field season and was provided by CoDA, founded by a group of faculties and researchers from University College Berkeley, USA and established as a California 501(c)3 nonprofit organization in April 2011. What was most spectacular about this approach was how their data flowed using CIDOC Conceptual Reference Model (CRM) to be published as linked open data to the Semantic Web in real time.

The Priniatikos Pyrgos archaeological project has taken a similar approach where they also concurred that the FileMaker system was too isolated from other archaeological datasets. In his paper, Lynam (2015) describes the process of using ontologies to structure digital archaeological datasets for publication on the Semantic Web. Open data, linked data, and the Semantic Web fully mapped to CIDOC CRM. The CRM was originally conceived to manage museum and archive material, but its core set of classes and predicates are now extended to include structured archaeological data. The

key to the flexibility of the model states that material objects are transformed when they move from one context to the next, where archaeological context can then adopt different meanings as they are affected by one event after another. The introduction of these kinds of schematic relationships, integrating artifact, time, place, and location into a seamless whole, together with the automation of machine-driven processing, means that cultural heritage can be liberated in innovative ways, made visible across different domains, even across related professional sectors, and interrogated alongside similar datasets. Once the cultural heritage community has agreed on common ontologies, controlled vocabularies, or thesauri, this methodology, enabled by the Semantic Web, facilitates highly complex querying built upon the principles of open data and linked data practice.

Visualization platforms, augmented and virtual reality

With a responsibility to preserve heritage resources from the past and a commitment to present it to the public in the present, as well as the obligation to conserve and relay it to future generations, together with the ability to document, describe, and disseminate heritage resources over the Semantic Web, we are now poised to create new kinds of experiences that not only interpret, but celebrate heritage resources and make them accessible to all (see *DIGITAL MEDIA IN ARCHAEOLOGY*). Three-dimensional worlds can be created to recall lost histories; oral traditions can be recorded, reenacted, and shared from one community to the next and from one generation to the next, as tangible and intangible heritage can be augmented and reinserted into previously hidden, even lost narratives. With all this digital potential, there is nothing to stop the imagination, and human creativity, calling up compelling scenarios based on heritage resources from other times and distant places, to be transmitted over the holodeck of virtual reality. This section will discuss two examples from China and London, United Kingdom.

Created by Professors Sarah Kenderdine and Jeffrey Shaw at the City University of Hong Kong in 2012, *Pure Land: Inside the Mogao Grottoes at Dunhuang* is a 1:1 scale virtual facsimile that reframes and reconstitutes the extraordinary wealth of the seventh- and tenth-century paintings found in the caves at Dunhuang, created by, and in partnership with, the custodians of the Mogao Grottoes, the Dunhuang Academy. Regrettably, the Grottoes are threatened by rising levels of humidity and carbon dioxide due to their popularity as a tourist destination, and the virtual reconstruction offers a means of granting access to heritage resources without endangering the heritage itself. Incorporating laser scans of the cave architecture and high-resolution photographs, the augmented-reality installation generates a virtual reconstruction of a Tang dynasty cave, one of the world's great treasures of Buddhist art. The embodied encounter allows visitors to experience the architectural elements and the murals as if they were entering the cave themselves, and, due to the pictorial recoloring, digital enlargement, and a rich sound design, visitors can explore the cave as a multilayered, multimedia interactive drama. These kinds of heritage-driven narratives provide ground-breaking technological and operational opportunities for the future of digital preservation; a paradigm shift for the dissemination of heritage interpretation; and exciting new ways to experience embodied heritage resources.

Elsewhere, far away from the depth of the caves, visitors can explore heritage resources through a shift in time simply by walking down the street. Incorporating images by photographers Henry Grant, Wolfgang Suschitsky, Roger Mayne, and George Davison Reid from the Museum of London's extensive collections, and developed to mark the opening of the New Galleries of Modern London exhibition in 2011, Streetmuseum presents a hybrid perspective of historical and contemporary London. By pointing your smartphone at one of London's famous landmarks and selecting a destination from the London map or using your GPS to locate an image nearby, the app superimposes historic images of London over the present-day view. The Streetmuseum app now has over 100 locations and images, ranging from 1868 to 2003, offering historical

juxtapositions of London locations enhanced with historical information about each one. This digital window compresses time and space in a single swipe of the screen, and offers unique glimpses into many years of the city's tempestuous history.

These kinds of culturally enriched digital platforms not only sustain rich narratives but enable them to fold into heritage, or open up new pathways for self-directed learning and creative ways of thinking about self, past and present.

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Digital Media in Archaeology

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Archaeology is a discipline that from its very beginnings has depended on multiple media to convey the results of its research. The recording of archaeological excavations and finds has always been a visual process. Based on handwritten notes and sketches in diaries, archaeological recording was supplemented with the work of artists, architects, and surveyors, who created drawings, plans, and maps. Early photography was employed to create what was perceived as more “truthful” imagery of archaeological remains, and was part of empirical research that often combined archaeology with anthropologic and geographic exploration (Hannavy 2008).

The number of media employed in archaeology has risen exponentially with the increase in multidisciplinary and technical innovation. Photography, most often black-and-white photographs for printing and color slides to be used in lectures, became a mainstay for field and finds recording. Basic rules for photography were developed, so that each site photo had a scale and north arrow, while each object was photographed with a (color) scale from multiple directions (Bohrer 2011). Apart from architectural plans, the use of theodolites, and later total stations, enabled exact recording of the location of excavation trenches, walls, soil units, and (noteworthy) individual objects in situ (see TOTAL STATION). Methods were created for object drawing, standardizing the location of the light source (upper left corner) and shading (Griffiths, Jenner, and Wilson 2007), as well as the different views and cross-sections that needed to be drawn for each type of object. Ceramicists developed a drawing standard that included a reconstruction of the rim diameter and shape of the pot, based on diagnostic (rim, handle, and base) sherds. With an increased interest in methodology, the

purpose of drawings versus photographs was summarized in an ideal approach combining the two: photography was faster, but less engaged, while drawings enabled one to emphasize certain aspects and look at objects in different types of light, so details that could not be made visible in photographs could be filled out. Drawing also enabled reconstructions of objects, buildings, or entire ancient lifeways. Film and video were used sparingly in archaeology, mostly to record (or reconstruct) moments of spectacular discoveries, which was useful for fund-raising and informing the general public, but also to record the process of archaeology. Ethnoarchaeological research (see ETHNOARCHAEOLOGY) employed photography, film, and video widely to record aspects of present-day society that provide information on archaeological research questions often in support of analogical reasoning, but more successfully in attempts to counteract cultural limitations in understanding the past and undermining preconceived notions of the researcher.

Multidisciplinary teams, with specialists studying different materials or artifact groups and producing additional notes, photographs, and drawings, created a rich body of knowledge, which appeared difficult to cross-reference. Usually only the editor of the final publication would gain insight into the different lines of evidence. Multimedia were, therefore, closely linked to one of the last phases of the archaeological work: the publication. Text with a selection of drawings, photographs, and maps was part of every traditional archaeological publication, often divided into chapters per artifact group and ideally integrated in a final concluding chapter. The final phase of the archaeological research process, archiving, again split the various media up into slide libraries, map drawers, negative binders, and notebooks, due to the varying preservation requirements for each type of medium.

With the digital turn in archaeology, the multimedia landscape has changed dramatically. It is not just that digital photography is affordable and that the number of photographs typically taken by archaeologists has risen exponentially.

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It is not just that the traditional methods are becoming less relevant, with hand-drawing being replaced with photography or photogrammetry and specific lighting techniques, such as infrared photography and reflectance transformation imaging (RTI), that allow for a differentiation in lighting to bring out details that are not even visible with the naked eye. It is not just that three-dimensional (3D) modeling of ongoing excavations is adopted widely by using structure from motion (see *STRUCTURE FROM MOTION*), in which software is used to create the geometry of a landscape or object from photography. While these developments have altered the methods archaeologists employ to capture data, the most important change is that it has become feasible to integrate different digital media, and that photographs, drawings, maps, visualizations, and video are increasingly considered as information on equal footing with quantitative and qualitative data. Almost every excavation uses databases and spreadsheets, but, while possible, joining field information seamlessly with photographs, maps, and the study results of specialists frequently remains elusive. This is in large part because a digital excavation requires a specific and coordinated workflow to ensure that all types of information can be connected. One feature that all archaeological information has in common, for instance, is location. Geographic information systems (GIS) can be used as a basis, which allows for all aspects of an archaeological project to be linked, but photographs similarly can provide an entrance to the entire data landscape. Digital media thus form a network of interconnected data in many different shapes, but with one basic output: the screen.

Twenty-first-century archaeologists collect data in different forms for various purposes. Surveying results in a digitally born map (see *DIGITAL CARTOGRAPHY*) using total station or differential global positioning system (DGPS) points downloaded directly into the GIS. Apart from the traditional digital media, digitized texts, spreadsheets, databases (see *DATABASES IN ARCHAEOLOGY*), photographs, drawings, videos, and GIS, archaeological research also has to take into account increasingly large file types linked to documentation and analytical instruments, such as ground-penetrating radar (see *GROUND-PENETRATING RADAR*),

magnetometers (see *MAGNETOMETRY*), light detection and ranging (LiDAR) (see *LIDAR DATA VISUALIZATION AND PROCESSING*), 3D scanning (see *LASER SCANNING*), and other nondestructive approaches, as well as dating methods (see *DATING IN ARCHAEOLOGY*), scanning electron microscopy (see *SCANNING ELECTRON MICROSCOPY*), Raman spectroscopy (see *RAMAN SPECTROSCOPY*), X-ray diffraction, (portable) X-ray fluorescence spectroscopy (see *PORTABLE X-RAY FLUORESCENCE SPECTROMETRY (PXRF)*), and gas chromatography combined with mass spectrometry (see *GAS CHROMATOGRAPHY-MASS SPECTROMETRY (GC-MS)*), to name but a few.

As with traditional publication, most of this information comes together when the results of all participants are gathered, usually close to the publication date. Experiments with hybrid digital media publications are ongoing. Instead of selecting a few photographs, a printed or digital publication can link to a large number of high-resolution color photographs with the information of what they depict, and (perhaps most importantly) what the relevance is of their subject. Instead of printing a page-size map which can hold limited information, including expensive fold-outs or unattached easy-to-lose large-format maps, the text can link to an interactive searchable map online. Zoom level can be connected to a specific data density or data type and automatically display the information that is relevant to a particular scale. Instead of filling many pages with printed tables, an increasing number of publications link to online spreadsheets or databases. Where in the past reuse of information required the retyping of tables, with all the human reading and typing errors that such an exercise inevitably introduces, the future will hopefully bring a sturdy linked data landscape. Linked open data require information and knowledge to be exposed, shared, and connected on the World Wide Web using persistent unique identifiers (uniform resource identifiers (URIs)) and a conceptual framework to describe these resources (resource description framework (RDF)), organized through ontologies as part of the Semantic Web (see *SEMANTIC WEB AND ONTOLOGIES*) (Richards 2006).

The power and promise of digital media derives from the speed and efficiency at which connections can now be made among various

types of data, thereby creating a more direct path between field research, laboratory analyses, and dissemination. A further advantage, which is rapidly becoming the new normal, is that the original data output as well as the interpretation can be linked to a site report, the overall broader conclusions, as well as any other information relevant to the area or objects under investigation. Through the wide availability of digital media, publication has the potential to provide overarching conclusions that can be traced back all the way to the original observations, measurements, and interpretations, facilitating not only reuse of the data but also reproducibility of the results. This is extremely important for a discipline that considers itself a science, a social science, and a humanistic endeavor, often all at once.

There are several additional advantages to digital media publication. Moving beyond hypertext (the in-text clickable links), a connection of different media types forms a knowledge base that can be used in a nonlinear way. It frees the users from following the narrative in a text as determined by the authors. Images can function as an access point to the text and, similarly, map-based information and databases can be queried separately, providing insights and knowledge that go beyond what is presented by the excavators. This heuristic potential becomes even stronger if data from multiple projects are available and can be linked (Geser 2016).

The use of digital media in archaeology still presents considerable problems, which can only be solved if archaeologists are aware of and adhere to good practices. Much of the information is gathered with proprietary soft- or hardware. This means that such formats can only be shared if all users purchase the same equipment or use the same programs and platforms. Only if the package or instrument enables export in an open data format is reuse of the data and more importantly reproducibility of the results possible. This also requires being explicit about the method used, including the workflows, ways of measuring, tools, and algorithms. Much has been written about metadata, which is the information that describes in detail how we should understand the data. This includes, for instance, the name of the person who took the photograph, did the measurements, and wrote the interpretation, but also to what these data pertain exactly. The long-term

preservation of digital research data is as yet uncertain. For archaeological data this is particularly urgent, because the mere activity of excavation destroys the layers that contain the information on which our interpretations and explanations are based. The importance of the preservation of digital archaeological research in its many forms is gaining recognition. There are two major repositories for archaeological data—the Archaeological Data Service (ADS) in the United Kingdom, and the Digital Archaeological Record (tDAR) in the United States—that offer not just data back-up, but also migration to new versions of software and hardware systems. There are several publication initiatives that team up with these and other repositories (such as university-based digital libraries). Examples of these are the Digital Information Gateway (DIG) (<http://dig.ucla.edu/project>), Internet Archaeology (<http://intarch.ac.uk/>), the Journal of Open Archaeology Data (JOAD) (<https://openarchaeologydata.metajnl.com/>), Open Context (<https://opencontext.org/>), and Advances in Archaeological Practice (<https://www.cambridge.org/core/journals/advances-in-archaeological-practice>).

Apart from the uncertainties around preservation, there is a continued need for a critical approach to the perception of different media. Many of these concerns are no different than those pertaining to the traditional information, and specifically the visual aspects of traditional multimedia. Photographs and video have mistakenly been considered as objective records of a given situation, while they convey the literal and mental viewpoint of the photographer (Bohrer 2011). It is not just the camera position that influences how we see through the lens of the film or video camera, but also whether we are shown the world in overview or close-up. What is excluded from the image is sometimes as important as what is included. During editing, the entire narrative can be changed from what the original situation was. Interventions such as changing the order, adding a speaker's words to a different bodily attitude or facial expression, or adding voice-over or music all result in a particular understanding and interpretation of the visual media.

Visualizations are persuasive and strongly influence the understanding and memory of what is depicted (Molyneaux 1997). Much of this understanding is subconscious, and even

if the author explicitly writes a disclaimer next to an interpretative illustration, the text will not affect the memory as strongly as the image. This is especially true for interpretations and reconstructions, but also the visual representation of archaeological data is far from objective. Charts or maps can give accidentally misleading impressions or provide the opportunity for outright manipulation (Monmonier 1991; Tufte 1990; Wendrich 2010).

These caveats are no different for digitally born representations, although the availability of the original data provides users with the capability to check data visualizations. That does not, however, guarantee the quality of the data themselves. Tools that routinely spit out digital results, such as automated survey or geophysical instruments, are a black box that might generate nonsensical results if the user is not aware of the process and lacks the ability to estimate what outcome is expected. A lack of awareness of how these black boxes are generating their output sometimes results in adjusting parameters based on biases, instead of understanding the mathematical or algorithmic processes.

The future of digital media is not necessarily completely born-digital. Creating illustrations and plans by hand still has its use, especially in the context of training and archaeological field schools. Drawing by hand forces the archaeologist to pay close attention. This not only repeats observations done during excavation, but often allows new or corrected results. Drawing requires a scrutiny and precision that is not equaled by photography. Those hand-made drawings can be digitized and incorporated in a rich data landscape. With the fast-growing capabilities of digital visualizations the next step will be an “immersive archaeology” where excavation data, interpretations, and reconstructions can be explored in a virtual reality environment (see VIRTUAL REALITY MODELING). Such a 3D representation of the world based on archaeology has an even stronger level of intrusiveness in the brain than drawings and requires a firm grounding in the data that we have, as well as an indication of the information that we do not possess. The heuristic power of digital media needs to be clothed in a careful presentation of data. In this respect, the terms *metadata* (the information that says something about another data carrier, such as a photograph

or a table) and *paradata* (the information that underlies a reconstruction, such as antique paintings or descriptions of ancient architecture) are not very useful categories, because data are agnostic of the use they are put to. Depending on our research question, all types of data can provide relevant information and all types of data are a form of digital media.

Digital media have the potential for broad distribution, which opens up access to archaeology outside the European/North American academic world and communities of nonprofessional audiences. Digital media can thus support efforts to bring archaeology into the community (see HERITAGE AND COMMUNITY ARCHAEOLOGY) and can help decolonize archaeological practices: The availability of all information will provide the avenue to check reports with a critical research approach, so that biased interpretations can be pointed out. The promise of digital media can, however, only be realized if the archiving problem can be solved and if archaeologists no longer consider data sharing as a gesture of generosity, but as an obligation of research groups and as a fundamental outcome of archaeological work.

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Distance and Data Transformation

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In archaeological sciences, data of various kinds are collected and/or measured in order to be evaluated properly by multivariate statistical methods. Usually, these data are organized as a matrix $\mathbf{X}$ with I rows that correspond to archaeological objects, and J columns (variables) that correspond to attributes describing the archaeological objects. These may be glass, metal and ceramic artifacts, Mousterian bifaces, archaeological deposits, inscriptions, images, skulls, pottery, ancient Roman bricks or tiles (Mucha, Bartel, and Dolata 2008). Attributes of such artifacts may consist of quantitative measurements such as chemical composition, and/or categorical data such as color. A special case is binary data such as absence/presence or yes/no.

The concept of distance (dissimilarity) is about quantification of how far apart any two archaeological objects are. Various distance measures can be applied to quantitative and/or categorical data. By using these pairwise distances, cluster analysis can find groups in data. Interestingly, special pairwise distances are an essential part of multivariate methods such as principal component analysis (Euclidean distance) and correspondence analysis (Chi-square distance).

A typical process of data clustering is demonstrated in Figure 1 with distances as a key feature. In the first row, the data matrix $\mathbf{X}$ represents objects (here: reliefs of gods of the Lion Temple at Musawwarat es Sufra in Sudan) and binary attributes (0 = absence, 1 = presence). The dendrogram visualizes the hierarchical clustering of these objects based on their pairwise distances (lower triangle of the $(I \times I)$ – matrix $\mathbf{D}$, due to

symmetry). This visualization of the hierarchy of clusters reveals at least two groups of gods, namely {27, 16, 14, 4, 26, 15, 2, 6, 5} and {10, 9, 22, 13, 12, 20, 19, 7, 18}. In the last row, hierarchical clustering of the attributes based on their pairwise distances is shown. Again, there are at least two groups of attributes, namely {V3, V2, V4, V6, V5, V10} and {V11, V12, V15, V17}.

The term distance (or dissimilarity) could have numerous meanings. The *Oxford Advanced Learner's Dictionary* defines distance as “[amount of] space between two points or places”, and it denotes distant as “(sometimes used with measurements) far away in space or time”. However, it denotes dissimilar as “(from/to sb/sth) not the same, unlike”. It is quite common to measure the distance between two points i and h on a plane with a ruler. Alternatively, if the coordinates of these points (x_{i1}, x_{i2}) and (x_{h1}, x_{h2}) are known, the corresponding (Euclidean) distance in the R^2 space is simply determined by:

$$d(i, h) = d_{ih} = \sqrt{(x_{i1} - x_{h1})^2 + (x_{i2} - x_{h2})^2} \quad (1)$$

The Euclidean distance complies with the (general) mathematical definition of a distance function.

A distance function d on a given set X (object space) is defined as $d: X \times X \rightarrow R$ (wherein R is the set of real numbers) fulfilling the following conditions ($i, h \in X$):

- (D1) $d(i, h) \geq 0$ (non-negativity)
- (D2) $d(i, i) = 0$ (distance of an object to itself is zero)
- (D3) $d(i, h) = d(h, i)$ (symmetry)

The latter means that the distance between i and h is the same in either direction. If, in addition,

- (D4) $d(i, h) = 0$ if and only if $i = h$ (principle of identity)

and d fulfils the metric (triangular) inequality ($i, h, m \in X$):

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$$(D5) d(i, h) \leq d(i, m) + d(m, h)$$

then it is termed a metric distance function, or, in short, a metric. The Euclidean distance is a metric, and so it allows a geometric interpretation such as: the direct way from i to h is the shortest. Generally, given an $(I \times J)$ – data matrix $\mathbf{X} = (x_{ij})$, the Euclidean distance between objects i and h is:

$$d_{ih} = \sqrt{(x_{i1} - x_{h1})^2 + (x_{i2} - x_{h2})^2 + \dots + (x_{ij} - x_{hj})^2} \quad (2)$$

The Euclidean distance given in Equation 2 is an appropriate measure in the case of measurement data. Such a distance function maps the dissimilarity of two arbitrarily high-dimensional vectors of the space R^J as a (single) real number. Whatever the number of dimensions (attributes) J may be, the outcome is a scalar that becomes a single element of the $(I \times I)$ – distance matrix $\mathbf{D} = (d_{ih})$. Comparatively, the human eye, particularly that of the archaeologist when sorting or reordering, is capable of perceiving distances of objects in one, two, and even three dimensions, but, hardly in higher-dimensional spaces.

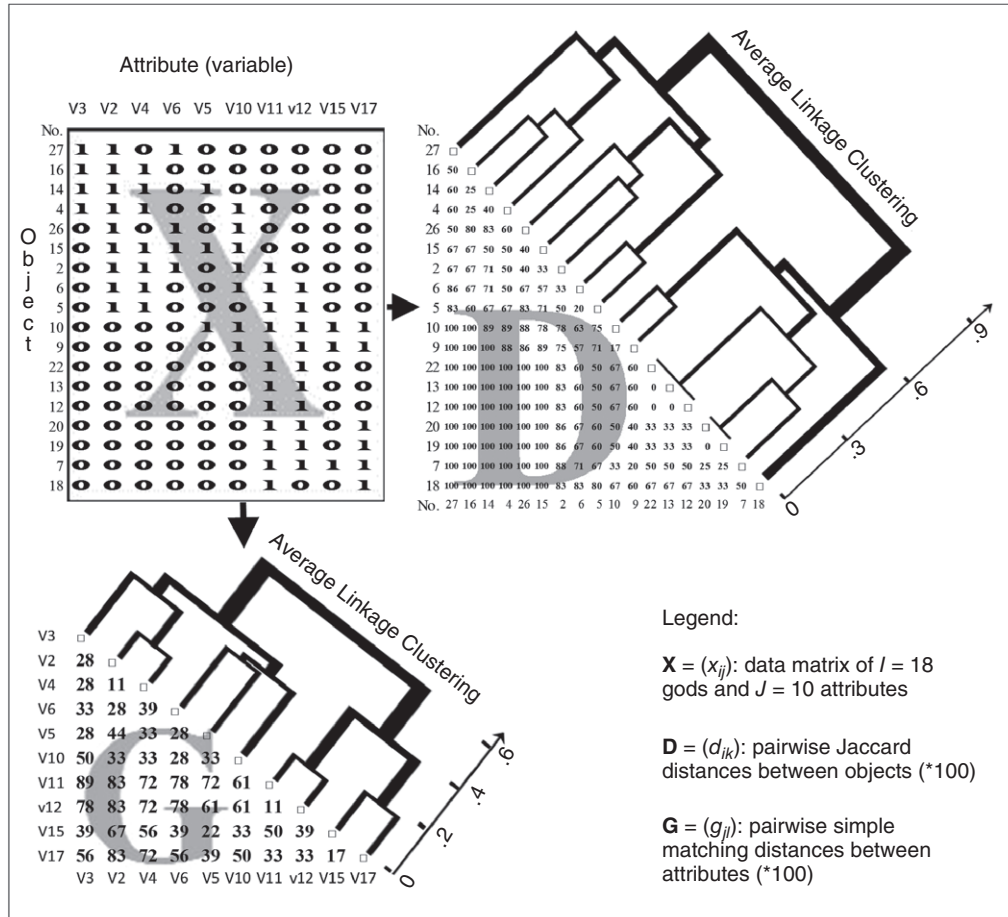


Figure 1 A typical application of distances in the context of data clustering. Given a data matrix $\mathbf{X}$, the clustering of the objects is based on the Jaccard distance in Equation 3 followed by the hierarchical average linkage clustering (Everitt et al. 2011). In a similar manner, the hierarchical average linkage clustering of attributes is applied on the base of the distance matrix $\mathbf{G}$ between attributes. Here the simple matching distance from Equation 4 is applied.

In applications to archaeometry, the distance measure has to be fixed very carefully for the mapping of high-dimensional vectors to a scalar. So, it may need meticulous efforts to choose an appropriate distance function for the data, because otherwise a distance function can yield misleading or even very dangerous results. First, the choice depends on the purpose of the considered multivariate statistical analysis, in other words, on the statistical model that has to be applied. Second, it also depends on the type of given data. Depending on the level of information (quantitative, categorical, binary, etc.), some of the most well-known distance measures are described briefly below.

Binary (or absence/presence or 0–1) data have the lowest level of information. Usually, the value 0 represents “false” (absence of an attribute) and 1 means “true” (presence). Oftentimes, the presence of an attribute is much more meaningful than its absence, as is the case in the archaeological data presented in Figure 1. Such an attribute is called asymmetric, otherwise symmetric. The Jaccard distance measure is a so-called non-invariant coefficient concerning symmetry with presence (=1) as the most important information. It is defined as:

$$d_{ih} = (\#_{10} + \#_{01}) / (\#_{10} + \#_{01} + \#_{11}) \quad (3)$$

where $\#_{10}$ counts the binary combination 1 (presence) and 0 (absence) of the two objects i and h across all J attributes; $\#_{01}$ counts the binary combination 0 and 1 of the two objects i and h ; and $\#_{11}$ counts the binary combination 1 and 1 of the two objects i and h , i.e., it is the number of 1–1 matches (or positive matches) across all J attributes.

Obviously, the higher $\#_{11}$ is in the denominator, the lower is the corresponding distance value. Here, the number of 0–0-matches (or negative matches) $\#_{00}$, counting the binary combination 0 and 0 of the two objects i and h , does not have any influence. Therefore, the Jaccard distance in Equation 3 is an appropriate distance measure that reflects the dominant importance of positive matches when assessing how distant any two archaeological objects are. For example, the Jaccard distance between objects 9 and 10 of Figure 1 is very small, namely $d(9, 10) = (0 + 1)/(0 + 1 + 5) = 0.167$. In contrast, the Jaccard distance between objects 10 and 27 is $d(9, 27) = (5 + 3)/(5 + 3 + 0) = 1$ (maximum). It should be mentioned that

the Jaccard similarity coefficient $s_{ih} = \#_{11}/(\#_{10} + \#_{01} + \#_{11})$ is more commonly known in statistics (Jaccard 1908), which is related to Equation 3, simply by $d_{ih} = 1 - s_{ih}$.

Other non-invariant distance measures for binary variables, for which the presence of attributes is more important, are:

$$d_{ih} = 2 (\#_{10} + \#_{01}) / (\#_{11} + 2 (\#_{10} + \#_{01})) \quad (\text{Sokal and Sneath})$$

$$d_{ih} = (\#_{10} + \#_{01}) / (2\#_{11} + \#_{10} + \#_{01}) \quad (\text{Dice})$$

The most important invariant distance measures concerning symmetry are:

$$g_{ih} = (\#_{10} + \#_{01}) / (\#_{10} + \#_{01} + \#_{00} + \#_{11}) = (\#_{10} + \#_{01}) / J \quad (\text{simple matching}) \quad (4)$$

$$d_{ih} = 2 (\#_{10} + \#_{01}) / (\#_{00} + \#_{11} + 2 (\#_{10} + \#_{01})) \quad (\text{Rogers and Tanimoto})$$

$$d_{ih} = (J - \#_{11}) / J \quad (\text{Russell and Rao})$$

$$d_{ih} = (\#_{10} + \#_{01}) / (2 (\#_{00} + \#_{11}) + (\#_{10} + \#_{01})) \quad (\text{symmetric Sokal and Sneath})$$

Clearly the Euclidean distance in Equation 2 is also an invariant measure for binary data, because it is related to the simple matching distance in Equation 4 simply expressed by $d_{ih} = (J g_{ih})^{1/2}$. That is of interest from a mathematical point of view.

Whenever the given binary data matrix contains both asymmetric and symmetric attributes, a distance value can be composed of a mixture of different distance measures, for example, the simple matching distance for symmetric situations and the Jaccard distance for the asymmetric ones. This is easily applicable since all the above-mentioned distance measures (except for the Euclidean one) are normalized in terms of their minimum (=0) and their maximum (=1).

Categorical data of attributes having more than two states—color, for example—are to be subdivided into ordinal or nominal data depending on whether there is an order of the states or not. In the case of K states, a practical simple way to deal with this is to split a nominal attribute into K

(new) binary variables. Here, each state defines its own binary variable. Then, the aforementioned distance measures can be applied to the new variables. Alternatively, distance measures based on the (original) nominal data are applicable, such as the (generalized) simple matching coefficient (Kaufman and Rousseeuw 1990). An ordinal attribute with K states looks like a nominal one, but the states, say the codes $1, 2, \dots, K$, define an order such as $1 < 2 < \dots < K$. Again, a practical way to deal with this is splitting it into K binary variables, but now in a different way in order to preserve the ordinal nature. Alternatively, distance measures for quantitative data such

as the city block distance (see below) can be applied.

The aim of cluster analysis is to find groups in data such as provenances of archaeological objects. The following example is taken from Baxter and Freestone (2006), where the complete original data matrix $\mathbf{X}$ is published. It will be analyzed hereafter. Each object is characterized by $J = 11$ attributes, namely the contents of oxides in percent. The sum of oxides of every object is 100%. The dataset of colorless Romano-British vessel glass contains two groups. Group 1 consists of 40 cast bowls with high amounts of Fe_2O_3 . Group 2 also consists of 40 objects: this is a

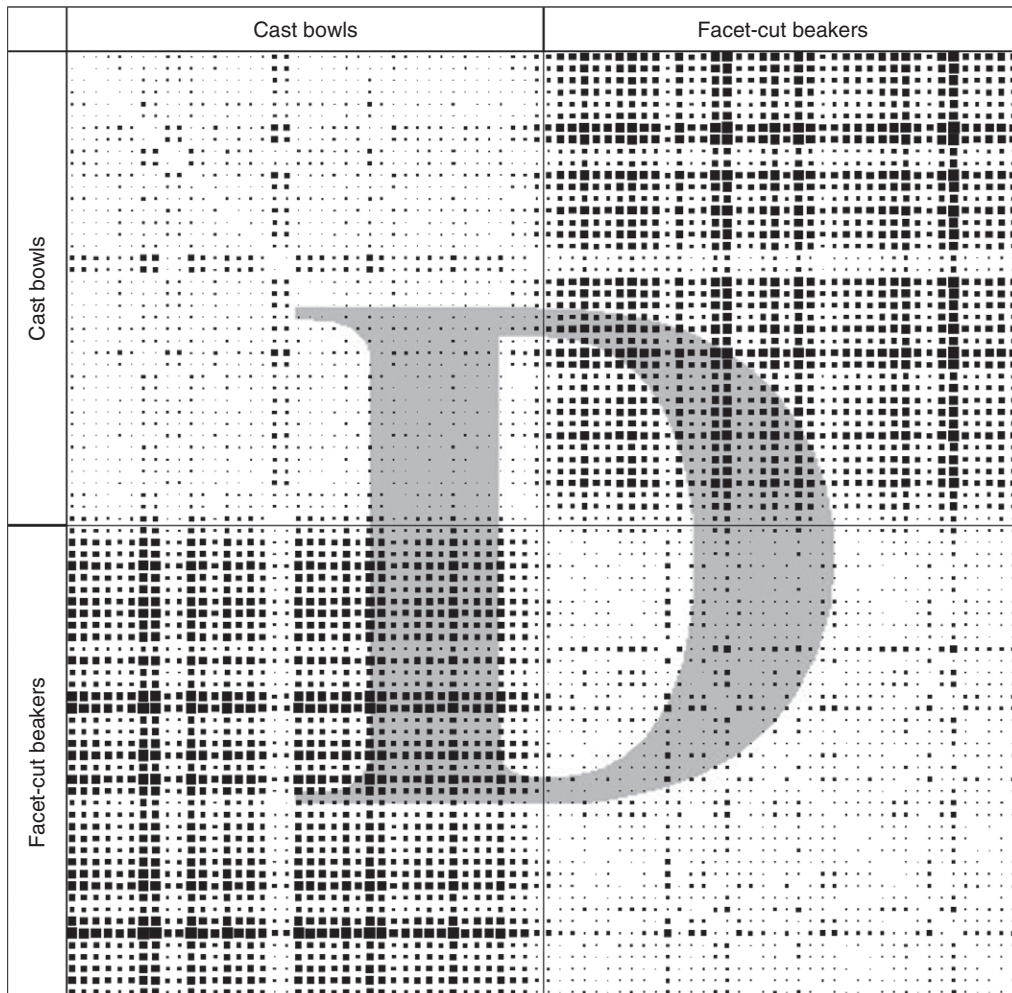


Figure 2 Heatmap of the Euclidean (80×80) distance matrix $\mathbf{D}$ of 80 colorless Romano-British vessel glass objects. The size of the black square in a cell is proportional to the corresponding distance value.

collection of facet-cut beakers with low Al_2O_3 . Figure 2 shows a special heatmap of the Euclidean distances between the objects. Here, the sequence of the objects in $\mathbf{D}$ is the same as in the original data matrix $\mathbf{X}$. Without any doubt, the heatmap makes clear that there are at least two clusters. Obviously, the distance between a cast bowl and a facet-cut beaker is large: see the bigger filled squares in the upper left region of the plot.

This plot can be improved significantly by ordering the objects in an optimal way and applying the Euclidean distances to logarithmic transformed data. The hierarchical minimum variance method (Ward 1963) finds the true groups without any error. Ward's method is based on the squared Euclidean distances. The reason is that merging any two objects i and h with the distance d_{ih}^2 to the cluster $\{i, h\}$ results in the within-cluster variance, which is simply $d_{ih}^2/2$.

In addition to the Euclidean distance, the city block distance between objects i and h :

$$d_{ih} = |x_{i1} - x_{h1}| + |x_{i2} - x_{h2}| + \dots + |x_{ij} - x_{hj}|$$

is one of the most well-known metrics. Both are special cases of the so-called Minkowski distance given by:

$$d_{ih} = (|x_{i1} - x_{h1}|^q + |x_{i2} - x_{h2}|^q + \dots + |x_{ij} - x_{hj}|^q)^{1/q}$$

where the parameter q is a real number larger than or equal to 1. There are a lot of other measures for metric data such as angular separation, Pearson correlation, and Canberra (Everitt et al. 2011).

A practical way to handle mixed data is converting them all into the binary form. Nominal or ordinal variables with K categories can be recoded into K (or $K - 1$ for non-dichotomous) binary variables. Continuous variables should be binned first into, say, K categorical (i.e., ordinal) variables and then recoded into K binary variables. In the case of many continuous variables, the number of binary variables will grow very quickly. Obviously, the downgrading of metric variables to binary variables means a loss of information in any case. Gower (1971) proposed a general similarity measure s that can be applied directly to mixed

data. From this similarity s , as usual, a distance measure can then be obtained simply by $d = 1 - s$.

Often, variables are measured in quite different scales such as percent, ppm (parts per million), or even ppb (parts per billion). Hence, some kind of data transformation is necessary since some distance measures such as Euclidean are not independent of the scale of measurements. Then, there is a need for appropriate data transformations in order to ensure comparability among the attributes so that the distances make sense. Moreover, data transformations such as logarithmic transformations could be applied to produce nearly symmetrically distributed variables, or to handle outliers (most extreme high values) in the data.

In the case of different scales, outliers, or long-tailed skewness of the distribution, a common approach is to transform the values for every variable into their rank values. However, the conversion of measurement data to rank order tables means losing a lot of information.

In statistics, the transformation of "raw" data (i.e., a given data matrix $\mathbf{X}$) into standard scores $\mathbf{Z}$ by $z_{ij} = (x_{ij} - m_j)/s_j$ is often recommended, where m_j is the mean and s_j is the standard deviation of variable j in $\mathbf{X}$. As a result, each new variable j in $\mathbf{Z}$ has a mean equal to 0 and standard deviation 1. Alternatively, the transformation $z_{ij} = x_{ij}/m_j$ can be applied to non-negative data (Underhill and Peisach 1985). As a result, each new variable j in $\mathbf{Z}$ has a mean equal to 1 but it has individual standard deviations s_j/m_j .

Often, the logarithmic transformation $z_{ij} = \log(x_{ij})$ is applied to data if all $x_{ij} > 0$. Otherwise, if some of the x_{ij} are zero, the transformation $z_{ij} = \log(x_{ij} + 1)$ should be applied. In the case of compositional data, a special data transformation can also be used: the so-called log-ratio transformation (Baxter and Freestone 2006). However, Mucha et al. (2008) showed that cluster analysis failed to find the true groups in the data shown in Figure 2 when the log-ratio transformation was applied.

SEE ALSO: Archaeometry; Cluster Analysis; Correspondence Analysis; Multivariate Analysis; Principal Component Analysis

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Exploratory Data Analysis (EDA)

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The most common approach in statistics is to test if a chosen hypothesis is true at a given probability level (see *HYPOTHESIS TESTING*). This is called confirmatory data analysis (Hoaglin 2006). When determining how to properly analyze any dataset, the first consideration must be the characteristics of the data themselves (Helsel and Hirsch 2002). Exploratory data analysis (EDA) minimizes prior assumptions and guides the choice of appropriate models for further examinations (Carranza 2009; Velleman and Hoaglin 1981). This statistical approach was developed in 1977 by John Tukey, who explained that its philosophy is to look at the data to see what they seem to be saying (Tukey 1977). In simple words, one could say that EDA is used for visualization and extraction of more substantive but less obvious information from the data. Indeed, EDA uses a wide variety of techniques (descriptive statistics (see *DESCRIPTIVE STATISTICS*) and graphical tools) for more effective exploration of a dataset. It is robust for the study of patterns, allowing us to visualize the structure of the data and to identify outliers (errors, peculiarities, or anomalies). These should be examined carefully in order to understand the dominant behavior and the unusual behavior in the data (Hoaglin 2006). EDA leads to a better understanding about what kind of advanced statistical methods should be applied to the data (Reimann et al. 2008). EDA also questions whether the scale in which the data are originally expressed is satisfactory. If not, a transformation (e.g., logarithmic) into another scale would benefit further analysis.

To summarize a dataset, Tukey (1977) recommends using descriptive statistics with the

five-number summaries based on sorting and counting. These numbers describe the data with values at selected depths: the central value is the median (Q2), the dispersion is represented by the minimum (Min) and the maximum (Max), and finally, the first quartile (Q1) and the third quartile (Q3) complete the description. The interquartile range ($IQR = Q3 - Q1$) measures the variation about the center of a distribution and is the most commonly used resistant measure of spread (Helsel and Hirsch 2002; VanPool and Leonard 2011). As the median is determined by the relative rank of the data, it is only minimally affected by the magnitude of a single observation. In most cases, this resistance to the effect of a change in value or presence of outliers is an advantageous property.

One way to visualize the five-number summaries is to use the Tukey box plot (Figure 1). A box is drawn from Q1 (also called the lower hinge) to Q3 (also called the upper hinge), crossing with a bar at the median. Two fences are defined according to their distance to the box. The first fences (inner fences) are one step (1.5 times IQR) outside the box, whereas the second fences (outer fences) are two steps (3 times IQR) outside the box. The whiskers extend to the value at each end closest to, but still inside, the inner fences (Tukey 1977). Values from the fences to either minimum or maximum are individually plotted so that data apparently straying out, far beyond the others, can be identified.

Box plots allow graphical representation of a dataset through the quartiles and thus provide information about the variation and central tendencies of data in a condensed manner (VanPool and Leonard 2011). It is a valuable tool to detect outliers, which are extreme values that can have several origins. They can be, according to Helsel and Hirsch (2002): (1) erroneous values (e.g., mistakes in measurements of an archaeological artifact); (2) observations from a population not similar to that of most of the data (e.g., data reflecting foreign provenance of some objects in a specific area); or (3) rare events from single populations that are skewed. It is very important to detect and examine outliers in order to

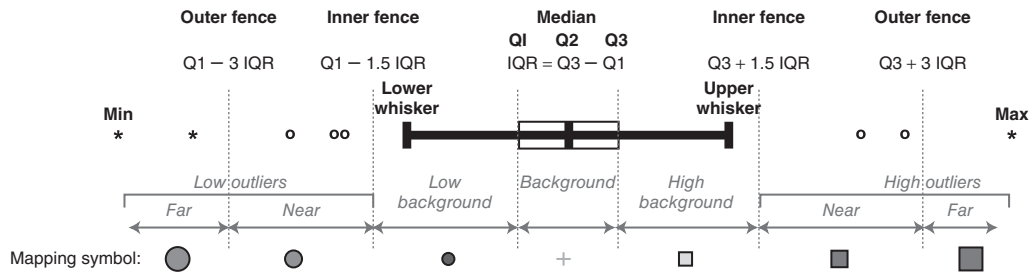


Figure 1 Tukey box plot used to describe a dataset with five-number summaries (Min, Q1, Q2, Q3, and Max). Whiskers correspond to the value at each end closest to inner fences. Seven categories based on the Tukey box plot and defined for mapping of geochemical anomalies are also specified.

determine if they should be excluded or treated with specific statistics. Box plots are excellent for the discrimination of properties within a dataset, even for comparisons between many groups of data. They are useful tools in determining whether medians, spreads, and symmetries differ among groups of data (Helsel and Hirsch 2002). Box plots, together with histograms and scatter plots are, among the EDA graphical tools, particularly used in any archaeological study.

Histograms provide a clear way of visualizing the frequency distribution of data in classes for a single variable (Figure 2, left). Bars are drawn with, on the ordinate, the number of data that fall into several categories on the abscissa. The histogram exhibits data structure, the central values, and the range per class. However, the visual display depends on the choice of the number of classes. The histogram permits at a single glance the detection of whether a data distribution is symmetrical or skewed. It is also readily apparent from a histogram if the data distribution is unimodal (with one peak depicting the presence of a single population) or multimodal (with several humps depicting the presence of several populations) (Reimann et al. 2008).

A two-dimensional scatter plot is an informative and simple graphic to study the relationships between variables (Figure 2, right). In EDA, data for two variables can be plotted to identify any unusual structures in the data (linear/curved, separate regions, variability in spread) and assist in determining which process could produce these unusual structures (Helsel and Hirsch 2002; Reimann et al. 2008).

Box plots are useful for comparing data for single variables, whereas two-dimensional scatter

plots illustrate relationships between two variables. However, it is also important to study relationships when there are more than two variables (which is often the case in archaeology). Several other tools/methods of EDA can provide insight into variable relationships, such as scatter plot matrix (Figure 2, center) and principal components analysis (see PRINCIPAL COMPONENT ANALYSIS) (PCA). PCA is a method to express differently the data. The PCA-transformed data are a linear combination of the original variables, uncorrelated and arranged in order of decreasing variances (Helsel and Hirsch 2002). PCA is dependent on the scale, so the transformation of data before analysis is of primary concern. This method is used to study correlations between the variables in large datasets, and to find which variables are redundant for further analysis. PCA helps to distinguish different populations and allows the identification of outliers. It is often used before a cluster analysis.

The EDA approach is widely used in various scientific domains such as environmental sciences, earth sciences, and economics, as well as in all the fields of archaeology. The work of archaeologists is indeed to analyze archaeological records (see ARCHAEOLOGICAL RECORD), behind which is the idea of describing, counting, and measuring these records, to categorize them in order to interpret function, provenance, or to a greater extent human behavior and culture (see ARCHAEOLOGICAL CLASSIFICATION). In other words, one of the archaeologist's objectives is to study the typology of artifacts through qualitative (e.g., color estimation) and quantitative (e.g., length and width measurements) variables. These typological studies can lead to the

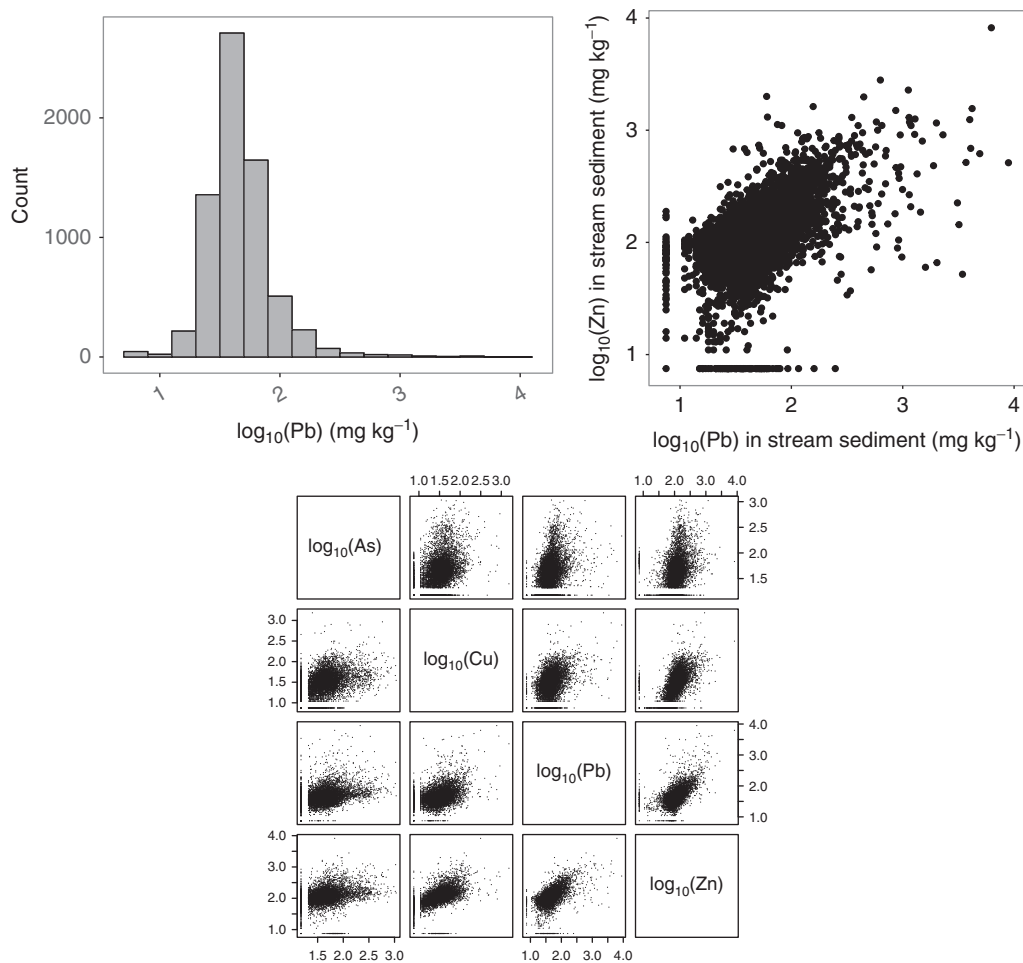


Figure 2 Three examples of EDA graphical tools: histogram (left), two-dimensional scatter plot (right), and scatter plot matrix (center).

Source: Geochemical data from the French geological survey (<http://sigminesfrance.brgm.fr/>). Graphics were created using R software (R 3.3.0, <https://www.R-project.org/>).

collection of large datasets. EDA is also useful when data are not sufficient for confirmatory data analysis, and this is important because sometimes archaeologists have to deal with limited/subset data (i.e., the study materials are only a portion of the past) (VanPool and Leonard 2011).

EDA applications in archaeological fields are numerous. EDA of the spatial distribution of chemical elements in archaeological soils helps to understand the function of specific areas. In anthropology and archaeozoology, the analysis

of morphological traits may help to study population movement. To study ceramic or lithic provenance, for example, with trace element and mineralogical analyses, archaeologists have to define potential subgroups. This can be done by combining several EDA tools such as bivariate plots, cluster analysis (see CLUSTER ANALYSIS), or compositional profile plots. These tools assist archaeologists in the first step to identify artifact composition groups and to partition a dataset into groups of samples that apparently have distinctive compositions.

An application of EDA is detailed here for the interpretation of trace metal anomalies as a tool for field prospection in mining archaeology. This case study illustrates the potential of EDA to assist explaining how geochemical anomalies in streambed sediments could help in tracing ancient mining sites. The study area is the French

northern Alps where several phases of mining occurred from the Bronze Age to the twentieth century. The mining sites are spread all over the territory and various substances were exploited including iron and lead (Figure 3, left). The exploitation of mineral deposits may considerably extend mineral dispersal, thus causing persistent

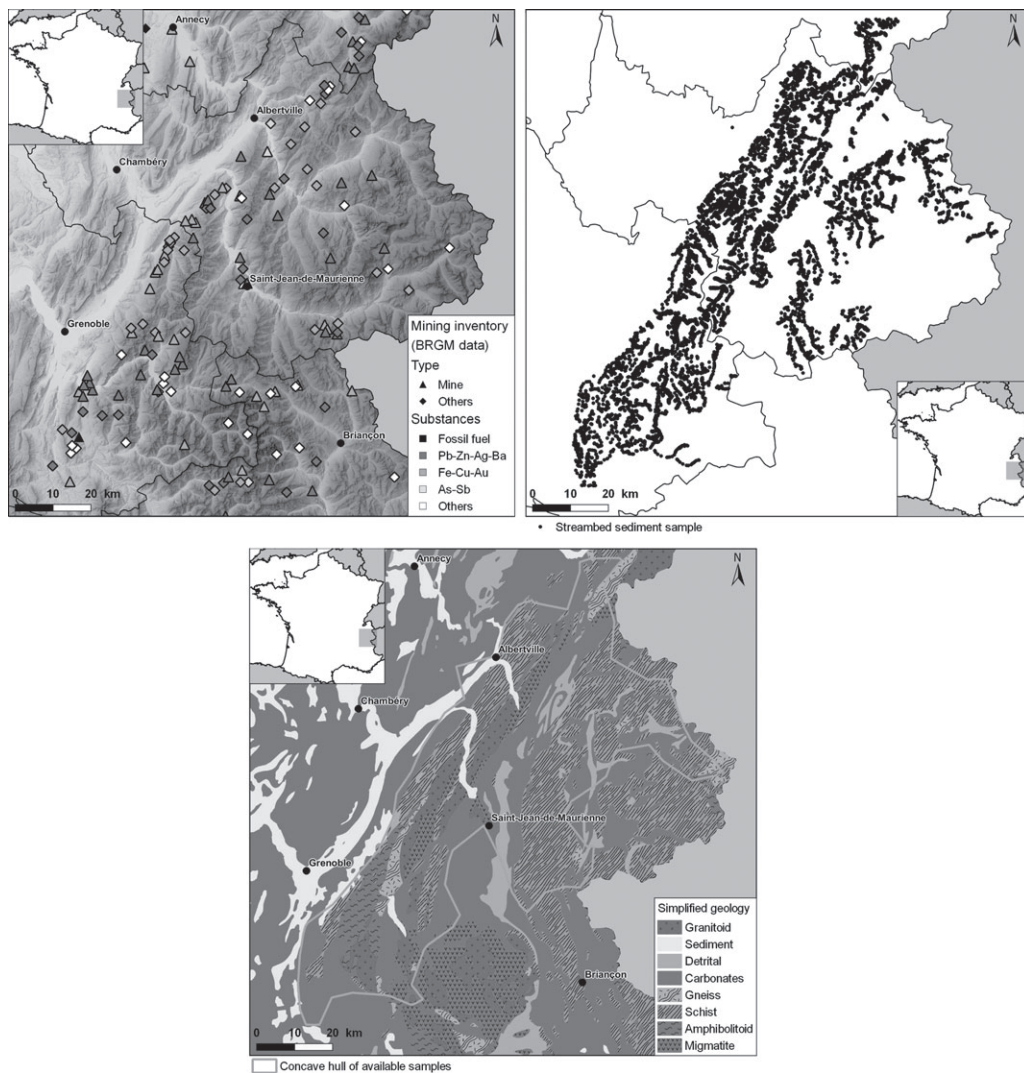


Figure 3 Inventory of mining sites in the French northern Alps (left), location of streambed sediment samples in the same area (right), and simplified map of lithological units (center).

Source: Data (geology, mines, and sediments) are from the French geological survey. Databases for the mines and streambed sediment samples are available at <http://sigminesfrance.brgm.fr/>. The maps were created using QGIS software (QGIS Essen 2.14.6, <http://www.qgis.org>), adapted by E. Camizuli from © IGN-2017.

local trace metal anomalies. The underlying idea of this case study is that streambed sediments represent composite erosion products of terrains outcropping in the catchment area. There are thus ideal proxies for studying the spatial repartition of ancient mining sites according to geochemical anomalies.

In the 1980s, the French geological survey (BRGM) performed a national inventory of mineral substances (<http://sigminesfrance.brgm.fr/>), leading to a huge amount of geochemical data. In the French northern Alps, 6,892 streambed sediment samples were collected (Figure 3, right), sieved at 125 μm , dried, and analyzed by direct current plasma for elemental compositions. For this case study, we focus on lead (Pb) concentrations because this element is known as a persistent pollutant, causing harmful effect (Kabata-Pendias and Mukherjee 2007). Since the first evidence of mining and metallurgical activities, large amounts of metals including Pb have been emitted into the environment. Lead is known for its low mobility in the environment and can be trapped in soils and sediments for

centuries; this is thus an excellent choice to study the mining anomalies. Moreover, Pb is a chemical element commonly studied in archaeology, particularly in lake sediments or metal artifacts. The ratio of Pb isotopes is indeed used for dating, studying provenance, and identifying pollution sources.

Geological information is of prime importance as well for determining correlation of streambed sediment samples with underlying local lithology. Simplified lithological units in the study area were extracted from the 1:1,000,000 scale map of the BRGM (Figure 3, center).

The point is to determine threshold trace metal concentrations by EDA procedures so as to distinguish anomalies from the local geochemical background. Such anomalies could be related to certain lithology but also to mining activities. A transformation procedure was applied to the data before computing thresholds, to make comparable the streambed sediment samples coming from different lithological units. In short, the data were centered (subtraction) with respect to the median (*med*) and then scaled (division) with respect to

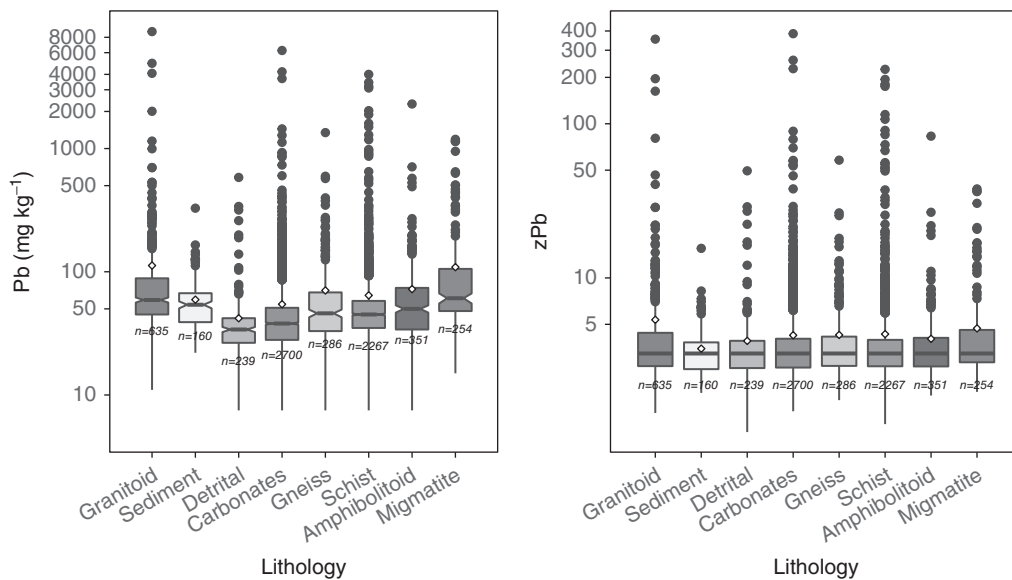


Figure 4 Pb concentrations in streambed sediments in the French northern Alps according to simplified lithological units.

Source: Original data (left) and standardized data (right) for EDA mapping (lithological data derived and modified from French geological survey 1:1,000,000 scale map). Graphics were created using R software (R 3.3.0, <https://www.R-project.org/>).

the median absolute deviation (MAD) for each lithology (j), thus:

$$Z_{Pb,j} = (X_{Pb,j} - med_{Pb,j}) / MAD_{Pb,j}$$

MAD is another resistant estimator of spread and is somewhat equivalent to the standard deviation (Helsel and Hirsch 2002). However, with the kind of transformation using the equation above, the transformed values can be negative and thus cannot be log-transformed. Another transformation was then applied to make all values greater than or equal to 1:

$$z_{Pb,j} = 1 + Z_{Pb,j} - \min(Z_{Pb,j})$$

Figure 4 illustrates the use of the above equations to standardize Pb concentrations (zPb) in

streambed sediments according to the lithological units.

Once the data are comparable, six Tukey thresholds were computed defining seven categories for EDA mapping: far and near low outliers, low background, background, high background, near and far high outliers (Table 1, Figure 1). The thresholds were calculated using the `map.eda7` function of the `rgr` package, supplementing the R software (R Development Core Team 2016).

Near and far high outliers are the two categories that are particularly interesting for highlighting ancient mining site areas. Computation shows that these categories represent 5.04 percent of the dataset (Table 1). It is easy to link each sample to the corresponding category, and, as each sample possesses coordinates, to

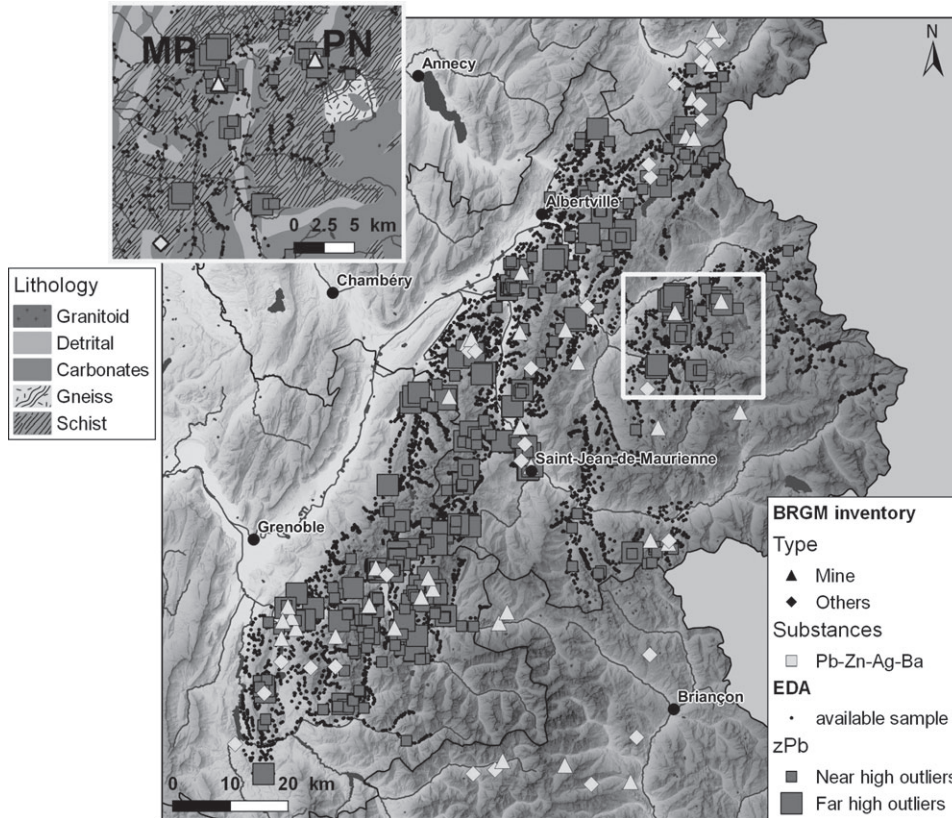


Figure 5 Mapping of high EDA anomalies in standardized Pb concentration (zPb), with data from streambed sediments in the French northern Alps. Also shown are Pb mining sites inventoried by the French geological survey. MP, Macôt-la-Plagne; PN, Peisey-Nancroix.

Source: The maps were created using QGIS software (QGIS Essen 2.14.6, <http://www.qgis.org>), adapted by E. Camizuli from ©IGN-2017.

Table 1 Ranges of the seven categories for EDA mapping, calculated from standardized Pb concentrations in streambed sediment samples, and their respective percentage in the whole dataset.

EDA category	Range (zPb)	Percentage
Far low outliers	≤ 0.75	0.00
Near low outliers	(0.75–1.41)	0.73
Low background	(1.41–2.65)	24.23
Background	(2.65–4.03)	49.58
High background	(4.03–7.5)	20.43
Near high outliers	(7.56–14.2)	3.34
Far high outliers	> 14.2	1.70

map them with the mining inventory (Figure 5). When focusing on an area with known mining activities, such as Macôt-la-Plagne (eighteenth to twentieth centuries) and Peisey-Nancroix (eighteenth to nineteenth centuries), it is easy to visualize their impacts. Areas with anomalies and unknown mining sites would be good candidates for prospecting if no other explanation for their presence can be found.

EDA is widely used by archaeologists to summarize and graphically display their data. These procedures and confirmatory data analysis complement each other. EDA results may stimulate further questions and lead to further analysis. If possible, data should be investigated with both approaches to avoid misinterpretation (Reimann et al. 2008).

SEE ALSO: Nonparametric Statistics; Statistics and GIS; Statistics in Archaeology

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Factor Analysis

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Factor analysis (FA), like principal component analysis (PCA), involves reducing the dimensionality of the measurement space computed over the dataset brought forward for analysis. The two differ by PCA typically being used in exploratory data analysis aimed at inferring patterning in the dataset brought forward for analysis, whereas FA involves confirmatory data analysis aimed at accepting or rejecting a model hypothesized to represent the patterning in the dataset.

Both procedures reduce redundancy in the dimensionality of the measurement space for the dataset. With archaeological data, dimensionality redundancy arises when the number of variables the archaeologist selects for measurement of artifacts over-represents the likely number of dimensions that were under control when making an artifact. For example, the projectile points from the 4 VEN39 site in Ventura County in California were measured using seven metric attributes, although it is highly unlikely that a producer kept seven dimensions in mind when making a projectile point.

With multivariate data, exploratory data analysis is often employed due to lack of adequate theories from which a model specifying the anticipated patterning in the dataset may be proposed. Dimensionality reduction also enables visual presentation of the data in the form of histograms for a single variable or scattergram plots in two or three dimensions. Both FA and PCA employ visual representation for discerning the structure of the data being analyzed.

Although dimensionality can be reduced by simply restricting the analysis to one or two variables at a time, patterning that involves several variables is then difficult to discern. Instead, dimensionality reduction is aimed at removing redundancy in the dimensionality of the measurement space for the dataset. For ratio-scale

variables this may be done with FA or with PCA. (Multidimensional scaling is used to reduce dimensionality with ordinal-scale variables and correspondence analysis does the same for nominal-scale variables, but these will not be discussed here.)

FA and PCA have the same underlying mathematical foundation for computing numerical information derived from the data brought forward for analysis that is central to these two procedures. This includes numerical information referred to as eigenvalues, component/factor loadings, and component/factor scores, depending upon which procedure is being employed (see *PRINCIPAL COMPONENT ANALYSIS*). Instead, the focus here is on the differences between FA and PCA from the perspective of exploratory data analysis versus confirmatory data analysis, so as to identify the reasons for using one technique or the other. In addition, an aspect relevant to both FA and PCA that has been insufficiently discussed in the literature, and is especially relevant to the use of FA or PCA with archaeological datasets, will also be discussed.

Reducing dimensionality involves a trade-off between, on the one hand, facilitating visual discernment of patterning, and, on the other hand, preserving as much of the numerical information embedded in the measurement space as possible. Both procedures involve (mathematically) determining a less redundant dimensionality for the measurement space as follows. Begin with a dimension corresponding to an axis in the measurement space along which variability in the data projected perpendicularly onto this axis is maximal among all possible axes for the measurement space. The next dimension corresponds to the axis perpendicular to the first axis along which the next greatest amount of variability in the measurement space occurs, and so on.

The axes are referred to as factors in FA, and principal components in PCA. Due to the way they are constructed, the first few factors in FA, or principal components in PCA, will encompass much, or even most, of the variability in the data being analyzed, thereby reducing the

dimensionality of the measurement space with relatively little loss of information. PCA and FA differ by the former being model-free and the latter model-based in the determination of these new dimensions. Being model-free means that, in PCA, as many principal components are determined as there are variables. Thus the original measurement space has simply been re-expressed with new dimensions corresponding to axes ordered according to the amount of variability in the data accounted for by each axis. In PCA, considering only the first few principal components for further analysis of the data reduces dimensionality. There are “rules of thumb” for deciding how many principal components should be kept.

Factor analysis differs from PCA by employing a model for the reduction of the dimensionality of the measurement space in which the variables being measured are deconstructed into two parts: the deterministic part and an error term. To illustrate, suppose (following the ideas of Rouse 1939) that potters first decide on the desired height of a pot and then on its diameter as a linear function of its height. However, errors in the diameter corresponding to the height occur while making the pots. We can model their ideas about these two pot dimensions by the equation $D = \alpha + \beta H + \epsilon$, where D is the pot diameter, H is the pot height, ϵ is the amount by which the actual pot diameter deviates from the potters’ normative relationship, $D = \alpha + \beta H$, and the values for the parameters α and β express the normative relationship they have in mind between H and D . If we assume that the errors in the diameter arising when making a pot are small and without directionality, then it follows that the ϵ values will tend to have a normal distribution with mean 0 (since there is no directionality) and standard deviation σ , whose magnitude expresses the care taken by the potters when making the pots.

With factor analysis, the model for dimensionality reduction expresses metric variables as being determined by factors, with fewer factors than there are variables. For example, suppose the five metric variables length (L), width (W), thickness (T), angle of the tip (A) and height of the base concavity (H) are measured over triangular-shaped, concave-based projectile points, and the archaeologist hypothesizes that three factors, size, shape, and hafting, determine

the values for these variables as follows: $L = \alpha_1 \text{Size} + \epsilon_1$, $W = \alpha_2 \text{Size} + \epsilon_2$, $T = \alpha_3 \text{Size} + \beta_1 \text{Hafting} + \epsilon_3$, $A = \gamma_1 \text{Shape} + \epsilon_4$, and $B = \beta_2 \text{Hafting} + \epsilon_5$. The model expresses how the value for each variable varies with the values of the three hypothesized factors. The model also illustrates possible variability in how factors may relate to variables: (1) a factor need not affect all of the measurement variables; (2) the same factor can affect more than one variable; and (3) a variable can be affected by more than one factor. The parameters express the hypothesized relationships that the producers “have in mind.” For each measurement variable, an error term expresses deviation in that measure due to the producer’s error when making a projectile point.

With FA, the dimensionality of the measurement space is reduced to the number of hypothesized factors. The error terms account for variability not expressed through these factors. The factors corresponding to each of size, shape or hafting is determined from the correlation (factor loadings) of the variables with the factors. According to the model, the factor corresponding to size should only be correlated with L , W , and T , the factor corresponding to shape should only be correlated with A , and the factor corresponding to hafting should only be correlated with T and H . The model is accepted only if it satisfies goodness-of-fit criteria, including the hypothesized pattern of variable-factor correlations and the assumption that the error terms tend to have normal distributions.

FA can also be used in a quasi-exploratory manner when there are no factors identified in advance and the goal is to infer possible factors determining the variable values. Here, the model will express each variable as a linear combination of the possible factors and an error term. The number of factors must be estimated, but this depends on knowing the variance of the error terms, and the latter cannot be determined unless the number of factors is known. A number of approximations have been devised to help to resolve this indeterminacy.

Once the number of factors is estimated, then the pattern of factor loadings (correlations of variables with factors) is computed and used to infer what a factor seems to measure. A commonly used procedure to help infer what are the underlying factors is to rotate the axes in the

reduced measurement space so as to obtain factor loadings as close to 0 or 1 as possible. What is conceptually common to the variables all having a loading of 1 on a factor and a loading of 0 on the other factors would, presumably, be what that factor is measuring.

Probably the most renowned attempt in archaeology to use factor analysis to determine underlying factors was the attempt by Binford and Binford (1966) to infer toolkits as the factors underlying the frequency counts for tool types (based on Bordes' typology for Mousterian stone tools) found in Mousterian sites from Europe and the Middle East. They hypothesized that a factor would be a toolkit composed of the tool types used in a particular kind of activity. The tool type frequencies in a site would then be the consequence of the frequency with which an activity associated with that toolkit occurred at a site.

Their use of FA in this manner was heavily critiqued, and the notion of determining toolkits through FA has largely been dropped. However, the criticisms mainly related to technical issues that can be resolved. But a deeper problem with most archaeological datasets affects not only the use of FA (or PCA) for inferring underlying factors thought to be the drivers of the values for the measured variables, but virtually all statistical methods.

The problem stems from the fact that when statistical methods are used inferentially rather than descriptively, there must be homogeneity in the dataset brought forward for analysis; that is, all data values must arise through the same model with the same parameter values. This assumption was violated in the factor analysis of the Mousterian data, both by including each excavation unit in a site as an independent observation, and by the assumption that precisely the same relationship between tool types and toolkits held at all sites in Europe and the Middle East.

The difficulty that arises, in general, with archaeological data is that the dataset brought forward for analysis is typically heterogeneous and so an initial analytical goal should be one of partitioning the dataset into homogeneous subsets (see Read 2007; 2014) that are then to be used in further analysis. The problem with using heterogeneous data when inferring factors (or principal components) is illustrated in Figure 1, where the factors for the dataset as a

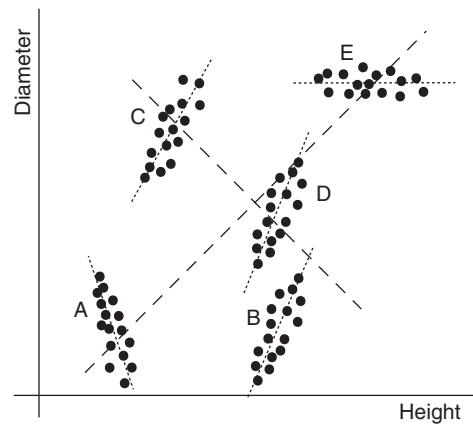


Figure 1 Heterogeneous dataset consisting of five subsets. Factors (dashed lines) for the dataset as a whole correspond neither to the factors for each of the subsets (dotted lines) nor to these subsets being one-dimensional. Subset A: diameters decrease with height. Subsets B–D: diameters increase with height in the same manner. Subset E: no relationship between diameter and height.

whole do not correspond to the factors computed on each subset separately. Thus the factors derived from considering the dataset as a whole may not have any archaeological meaning, contrary to the rationale for conducting the factor analysis.

The factors determined through FA or inferred through PCA assume homogeneous datasets with regard to the posited factors, hence the need to subdivide a heterogeneous dataset into homogeneous subsets with respect to the posited factors. However, transforming a heterogeneous dataset into homogeneous subsets incurs the “double-bind” problem discussed in Read (2014), since the criteria used to identify homogeneous subsets depends on already knowing the dimensions along which heterogeneity occurs, except in low-dimensional measurement spaces for which visual methods such as histograms or scatter-gram plots may be used to detect heterogeneity visually. For higher dimensional measurement spaces, ways to resolve the double-bind problem are discussed in Read (2007; 2014). The problem with heterogeneity of the data making up the dataset brought forward for analysis is common to all statistical methods in which the goal is inferential and not just descriptive.

SEE ALSO: Cluster Analysis; Compositional Data Analysis; Computer Applications in Archaeology; Correspondence Analysis; Inferential Statistics; Instrumental Analysis of Lithics; Principal Component Analysis; Statistics in Archaeology

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Fractal Models

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Fractal models are used to describe complex objects of irregular shape and nonlinear dynamic systems in physical and social spaces. Since these objects and systems have non-Gaussian statistical properties, the related studies require more sophisticated approaches (see POISSON AND BINOMIAL DISTRIBUTION AND STATISTICS IN ARCHAEOLOGY). Over the last 50 years, fractal models have been intensively applied in scientific fields including mathematics, physics, economics, biology, geomorphology, geography, computer sciences, cosmology, medicine, spatial demography, and linguistics. They may be applied to describe a wide range of structures and processes, from rocks and spatial perimeters to the turbulence and dynamic behavior of markets.

Introducing the term *fractal* into scientific circulation, Benoit B. Mandelbrot derived it from Latin *fractus*, meaning *fragmented* and *irregular*. Mathematically it is defined as a set for which the Hausdorff dimension strictly exceeds the topological dimension (Mandelbrot 1983). The Hausdorff (or fractal) dimension (D), the major statistical property of fractals, is estimated as follows:

$$D = \frac{\log p}{\log s}$$

where p is the number of self-similar portions and s is the scaling ratio of the portion to the whole. Any set with a non-integer dimension is a fractal. However, some examples of fractals with an integer dimension are also known (Mandelbrot 1983).

Since this mathematical definition is usually difficult for a wider audience, including social scientists, to understand, fractals are often introduced by their most important properties. Being scale-invariant and self-similar, a fractal as a whole may be studied through the analysis of

its portion. However, in numerous cases similarity between the smaller and larger portions does not mean that the former is just composed of scaled identical copies of the latter, or vice versa. Mandelbrot suggested the distinction for self-similarity and self-affinity defined as, respectively, invariance in changes in size or invariance in more than one scaling factor.

The scaling relationship in the size of portions of a fractal (p) is expressed by the power law function:

$$f(s) = kp^a$$

where k is the normalizing coefficient and a is the exponent that describes the behavior of a system; k and a are the constants. The smallest value of p , the initial point of the growth of a fractal, is called the initiator, while the power law function, the algorithm producing this growth, is called the generator (Mandelbrot 1983). In the case of self-affine variations, the structure of their outcome, called a multifractal, is operated by more than one power law function.

It should be noted that the scaling relationships expressed as power laws, also known as allometric growth models or Horton ordering process, were observed and applied to models describing the distribution of quantities in the physical and social spaces independently of Mandelbrot's work. Initial studies also questioned the similarities and differences between fractal relationships observed in physical and social systems. This early work may be exemplified by the size–frequency distribution of urban population, known as Zipf's law, or the magnitude–frequency distribution of earthquakes, known as the Gutenberg–Richter law.

Behavior in some complex dynamic systems combines the properties of chaos, or the highly sensitive dependence upon initial conditions, and fractals. The most widely known examples of this are the self-organized criticality and bifurcation diagram of the logistic map. Self-organized criticality is a property of complex dynamic systems that are driven to critical states or phase transitions (transformation of the properties of a system) by their internal

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development alone. In these instances, no external inputs are required. Fractals, including the aforementioned models for the distribution of earthquakes and urban populations, can be viewed as an outcome of intermittent phase transitions within a self-organized dynamic process (Bak 1996). Robert May and Mitchel Feigenbaum, in the fields of theoretical ecology and theoretical physics, respectively, independently investigated the complex behavior derived from the first-order difference equation of the so-called logistic or S-shaped growth. Such growth is characterized by a transition from simple periodic behavior to aperiodic regimes of growth with period doublings. This model describes the behavior of numerous complex dynamic systems, including population growth.

Research on fractals in archaeology and anthropology was pioneered by Ezra B. W. Zubrow (1985). Providing a theoretical and methodological framework for the new ideas exemplified by the case studies, he suggested five broad areas for the application of fractal models to archaeological records:

- Measurement of structures that cannot be distinguished from one another topologically, including the parameters of artifacts (see *ARCHAEOOMETRY*). Considering fragmentation as an inherent property of archaeological data (see *MATERIAL CULTURE*), application of fractal models allows for filling gaps in information derived from the sampled data (see *SAMPLING THEORY*).
- Simulation of complex phenomena, including the evolution of culture.
- More precise description and interpretation of the perimeters of spatial objects.
- Re-assessment of the application of well-known spatial models developed in analytical geography, such as Central Place Theory, nearest neighbors analysis, and the rank-size rule (see *SPATIAL ANALYSIS*), to archaeological records within a context of non-Gaussian statistics.
- The ability to deal with complex patterns, including applying fractal algorithms to the measurement of complexity.

Subsequent studies in these areas resulted in significant achievements, while the large number

of related research reports already necessitated extensive literature reviews at the beginning of this century. The topics highlighted by Zubrow are also closely related to the field of network analysis, which has been widely applied to archaeological data in recent years (see *NETWORK SCIENCE*). Particularly, the statistical properties of scale-free networks are described by the power law function (see Bentley and Maschner 2003 for overviews and case studies).

Fragmentation of artifacts, such as ceramics and tools made of flint and stone, showcase fractal properties (see *POTTERY DATA QUANTIFICATION* and *LITHICS DATA QUANTIFICATION*). For instance, the size–frequency distribution of pottery sherds and unbroken vessels, as well as flakes and tools made of flint and obsidian, is expressed by the power law function (see Brown, Witschey, and Liebovitch 2005; Zubrow 1985). This property is also found in the distribution of the volume of pottery. Application of fractal models to sets of artifacts extends the number of statistical tools used to simulate the intensity of artifact use and discard rates; this enables estimation of the number of pots or flint tools that were in use contemporaneously, leading to new perspectives on production and distribution (see *POTTERY DATA QUANTIFICATION*). This also provides a non-Gaussian way of estimating the level of repetitiveness of a sample in relation to the whole system (see *SAMPLING THEORY*), while also linking the analysis of initial archaeological data with the overarching economic and demographic phenomena.

Fractal properties are noted for the shapes of certain objects of monumental architecture (for example, pyramids) and settlement patterns, including the Ancient Maya cities. Since many features of the landscape, including geological structures and river networks (see *RIVER SYSTEMS*) are also fractals, the related analysis of settlement systems provides new perspectives on understanding human–environment interactions (see Brown et al. 2005; Zubrow 1985).

Fractal models are also applied to the developmental dynamics of social phenomena of the remote past. Some examples of these phenomena are culture change and evolution, stasis and avalanches in social and cultural development, interactions at different spatial scales, emergence of inequality, and ancient subsistence strategies

(see Barceló and Del Castillo Bernal 2016; Bentley and Maschner 2003; Brown et al. 2005 for the overviews and case studies). Work related to fractals includes the concept of self-organized criticality and the associated theory of punctuated dynamic equilibrium, hence contributing to method and theory in archaeology. In punctuated equilibrium, relatively long periods of stasis are interrupted by rapid bursts. These interruptions occur at critical points, where even small-scale disturbances can result in systemic imbalances (Bak 1996; Bentley and Maschner 2003). Therefore, the system state has to be considered in simulations and analysis of causal relationships between events.

Since the empirical basis for the fractal-like distribution of population has a long research history, the significant achievements of recent studies on population structure and land use are not surprising (see PALEODEMOGRAPHY and HUMAN POPULATIONS). For instance, Marcus J. Hamilton and his co-authors (2016) use fractals to demonstrate that social complexity emerges as early as in hunter-gatherer groups. Size of groups and population density follows the power law function. Moreover, a scaling ratio was found for hunter-gatherer spatial utilization, indicating that the size of the catchment area required by one person decreases as population density increases. Increasing density is further associated with a trend of decreasing annual movement. These results not only provide us with a mathematical description for the increase in complexity in relation to the balance between subsistence strategies, collaboration, and spatio-demographic structure of hunter-gatherers, but also allow for a hypothesis considering the transition to sedentism as a result of changes in subsistence ecology, rather than an increase in the number of people and population pressure (Hamilton et al. 2016).

DeLong and Burger (2015) consider population as a proxy for the total amount of energy produced by socioeconomic organization and environmental conditions that is consumed by human groups. According to their results, values of the exponent in the power law function that are lower than 1 characterize density-dependent growth, limited by a constant resource supply. Values approximately equal to 1 indicate exponential growth, while values exceeding 1 denote

super-exponential growth (DeLong and Burger 2015). Hence, the values of the exponent in the power law function represent a proxy for the increase or decrease in complexity.

As the majority of overviews on this topic remind us, despite the numerous fractals that are known, objects and systems of physical and social space have different statistical properties, and fractal models are applicable only to a part of them. However, measurement and explanation of those objects and systems that do exhibit non-Gaussian properties require the use of non-Gaussian statistical tools that have significant descriptive and analytical potential (see SAMPLING THEORY and STATISTICS IN ARCHAEOLOGY). Further work on fractal models in archaeology and anthropology opens new research perspectives on long-term development (see TIME AND TEMPORALITY), separating individual trends and general trajectories that appear to be far more complex than previously thought. These models yield fruitful results when they are used to explain the distribution of artifacts and their fragments, and may be applied to other problems connecting spatial objects to wider sets of data. This is also true for studies in population structure (see HUMAN POPULATIONS) and land use. Fractal modeling and the outcome of its applications has yet to be deeply integrated into archaeological method and theory.

SEE ALSO: Archaeometry; Hydrological Modeling; Mathematics; Measurement Theory; Poisson and Binomial Distribution; Predictive Modeling; Sampling Theory; Spatial Analysis; Statistics in Archaeology

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Geometric Morphometrics

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Geometric morphometrics are a class of multivariate methods for measuring and analyzing the shapes of objects. Geometric morphometrics are distinctive in that they use Cartesian coordinates (x , y , z) of landmark points in place of linear measurements as variables (Bookstein 1991). Most geometric morphometric methods use Procrustes superimposition to remove scale, rotation, and translation from the coordinates, which eliminates confounding effects of size, but which limits analyses to rigid objects. A wide range of multivariate statistical tests can be employed to assess the relationship of shape to other variables of interest (Dryden and Mardia 1998). One of the most popular features of geometric morphometric methods are that analytical results can be presented visually as deformations of objects instead of as tables of numbers.

Methodology

The hallmark of geometric morphometrics is that points on the surfaces of objects (or in their interiors, if volumetric data such as CT or MRI scans are available) are used to represent their shape. For example, the shape of a square might be represented by points at its four corners, or a Paleolithic hand axe might be represented by a series of points traced around its perimeter (see Figure 1a). The points may be two-dimensional (2D) or three-dimensional (3D), producing two (x , y) or three (x , y , z) variables respectively per point. In any one analysis, the same number of points must be placed on every object in corresponding locations and in the same order.

Three strategies for placing points can be distinguished. Landmarks, in the strict sense, are single points, each of which represents the position of a particular structure. For biological objects,

landmarks are usually placed at biologically homologous positions such as the junction between three bones or the openings of foramen (see Figure 1a, large circles). Landmarks can also be placed geometrically, for example at the point of maximal depth of the mandibular ramus. Semilandmarks are series of points arranged geometrically on a structure. Edges or curves can be represented by a string of semilandmarks, traced like a dotted line around them (see Figure 1a, small circles), and surfaces can be covered with a three-dimensional grid or cloud of semilandmarks. Like with landmarks, the ordering of semilandmarks on each object must correspond. For example, the 100 semilandmarks on the hand axes in Figure 1 all start at the midline of the base and trace the perimeter clockwise. Semilandmarks can be placed at regular intervals, or their placements can be optimized by sliding them until the shape differences between objects is minimized, a strategy known as “sliding semilandmarks” (Gunz, Mitteroecker, and Bookstein 2005).

Regardless of which point-placing strategy is used, point coordinates must be registered in a common coordinate system before analysis can proceed. Most geometric morphometric methods use generalized *Procrustes superimposition* to register coordinates (Rohlf and Slice 1990). In Procrustes superimposition, the coordinates of all objects are scaled, translated, and rotated to minimize the shape differences between them. Each object is centered on the origin ($x=0$, $y=0$, $z=0$), scaled so that the squared distances between each point and the origin sum to 1 (which is known as *unit centroid size*), and the objects are rotated about the origin until the *Procrustes distance*, or sum of squared distances between corresponding points between two objects, is minimized. This least-squares-fitting algorithm ensures that differences in shape are minimized or, in other words, that they are not due to spurious differences in orientation within the coordinate system, which is an important prerequisite for applying statistical tests for differences in shape. Procrustes superimposition has the statistical consequence of reducing the

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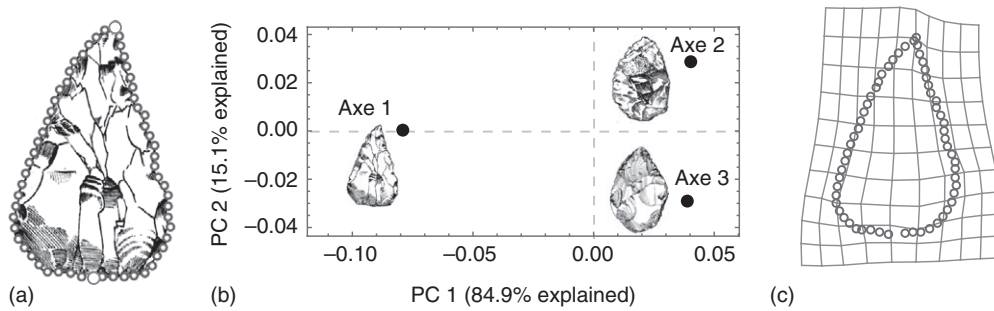


Figure 1 (a) Paleolithic hand axe with 60 semilandmarks placed at regular intervals around the perimeter (small circles) and two landmarks at the midline of the base and point (large circles). (b) The first two dimensions of a principle components analysis of the Procrustes superimposed coordinates of three hand axes. Axe 1 is the tool shown in (a). (c) A thin-plate spline diagram showing the shape difference between Axe 2 and Axe 1 as a deformation of the coordinates of the former into the latter. Modified from Smith, 1912.

degrees of freedom in the data by removing the effects of scale, translation, and rotation. Two-dimensional data are left with $2k-4$ degrees of freedom, where k is the number of landmark points, and three-dimensional data are left with $3k-7$ degrees of freedom. If the number of objects (n) in the analysis is less than these expectations, then the number of degrees of freedom is $n-1$.

Once superimposed, Procrustes coordinates are usually transformed into *shape variables* for further statistical analysis. Ideal shape variables are equal in number to the degrees of freedom and are orthogonal to (uncorrelated with) one another, but preserve shape differences between objects. The most common kind of shape variables are principal components (PC) scores (see Figure 1b). When based on the covariance method, principal components ordination represents a rigid geometrical transformation of objects to a new set of orthogonal axes whose number equals the statistical degrees of freedom of the data set. The coordinates of objects in the PC space, which are known as scores, are the shape variables. For example, the scores of Hand Axe 1 in Figure 1b are -0.08 on PC 1 and 0.00 on PC 2. Another commonly used shape variable are the *partial warps scores*, which are derived from an ordination of specimens based on the so-called bending energy matrix derived from spatial differences in the locations of points on the objects.

The principal components space is often viewed as a *morphospace*. Each point in the

multidimensional morphospace corresponds to a particular configuration of landmarks. Objects are placed at a given point when their shape corresponds to its particular configuration. Distances between objects in the morphospace are equal to the Procrustes distances between their superimposed landmark points if measured as a Euclidean distance calculated from the full set of PC scores. Principal component shape spaces are sample dependent in that their coordinate system is centered on the mean shape (the shape configuration represented by the point at the origin of the PC axes is the arithmetic mean of the Procrustes superimposed coordinates) and in that the first PC is oriented along the major axis of variation in the sample. If new objects are added, the distance between objects does not change, but the ordination of the axes and the values of the scores do.

Statistical tests and other kinds of analysis are performed on the matrix of shape variables. For the most part, any kind of multivariate statistical method can be applied to shape data, so long as the implications of the loss of degrees of freedom are taken into account (Dryden and Mardia 1998). Multivariate regression can be used to assess the relationship between shape and a continuous variable. For example, age-dependent changes in skull shape would be assessed by regressing shape scores derived from landmarks of the skull onto the chronological age of the individuals in the analysis. Multivariate analysis of variance (MANOVA) can be used to test for differences

between groups. For example, MANOVA can be used to test hypotheses that morphology is sexually dimorphic or that a new fossil sample is distinct from previously described species. Because shape variation often fails to meet the assumptions of traditional parametric statistics and because sample sizes in anthropology are often necessarily unbalanced, non-parametric permutation and Monte Carlo tests are to be preferred for shape analysis. When the objects being analyzed belong to more than one biological population or species, phylogenetic comparative statistical methods should be considered (Harvey and Pagel 1991).

Because the values of PC shape scores are sample dependent, it is perilous to try to interpret the causal relationship between just one principal component and an external factor (Polly and Motz 2016). For example, the arrangement of species along PC 1 in a shape analysis of tooth shape in monkeys may appear to correspond to the proportion of vegetation in their diets, but it is unlikely that the true relationship between tooth shape and diet corresponds precisely to that axis. Instead, a fully multivariate regression technique that utilizes the full set of shape scores from all PCs should be employed, not a visual inspection (or even a statistical analysis) of just one or two PCs.

Visualization techniques

Because shape variables directly correspond to Cartesian coordinates of points on objects, results from geometric morphometric analysis can often be presented as graphical depictions of the objects themselves. The difference between the shape of two objects, for example, can be illustrated as the displacement of landmark points. Interpolation methods such as *thin-plate splines* can use the landmark displacements to deform a grid in order to represent the deformation of one shape into another, a technique that has become one of the hallmarks of geometric morphometric methods (Bookstein 1991). For example, Figure 1c shows the difference between hand axes 1 and 2 as a thin-plate spline grid deformation of axis 2 into axis 1, which requires compression around the distal end to produce the latter's tapered outline.

While this example is applied to two objects, the same strategy can be used to show the difference between two group means (e.g., shape differences between sexes). Thin-plate spline grids are most effective with two-dimensional data. Results for three-dimensional data are often shown as animations of the change in shape along a linear trajectory through morphospace. Results from multivariate regression can be depicted the same way since the slope and intercept parameters it produces describe a line through morphospace.

History of geometric morphometrics

Geometric morphometric methods in the strict sense were first described in the late 1980s and early 1990s. Multivariate ordination and statistical methods had already been common since the 1960s (e.g., Blackith and Reyment 1971) and were applied to matrices of data such as linear measurements, angles, and areas. Statistical analysis of relationships between shape and other variables was possible using these methods, but interpretation could be difficult because size and shape were comingled and because the mapping of results onto biological form was usually interpreted by visual inspection of loadings of variables onto statistical factors. In a conscious attempt to capture the graphical power of the qualitatively estimated deformation grids that D'Arcy Thompson popularized in his book *On Growth and Form* (Thompson 1917), Fred Bookstein and others began experimenting with *truss analysis* of linear measurements that systematically connected landmark points in order to be able to transform factor loadings into a graphical map of which parts of the shape contributed most to differences between objects. The breakthrough came with the realization that Cartesian coordinates could be substituted for linear measurements and that thin-plate spline interpolations could then be used to produce deformable grids (Bookstein 1991). The addition of Procrustes superimposition as a tool to minimize shape differences as a prerequisite for statistical analysis (Rohlf and Slice 1990) completed the "geometric morphometric revolution."

Shortcomings

While geometric morphometric methods have many advantages over measurement-based methods, including the ability to mathematically factor out size and the ease with which results can be depicted graphically, they also have stubborn limitations.

Arguably the most constraining limitation is that the methods can only be applied to rigid objects. For the relative positions of Cartesian coordinates to be meaningful, each point used in an analysis must occupy a fixed position relative to all other points. The consequence is that objects that have mobile relationships to one another, such as mandible and cranium or body and limbs, cannot easily be analyzed with geometric morphometrics because spurious differences in their relative positions contribute to shape differences (e.g., the same individual would have a different “shape” if the limbs were moved to new positions). Special techniques such as two-block partial least squares can be used to analyze covariation in shape between objects that are not fixed, such as mandible and cranium, but these become cumbersome for systems involving more than two elements.

Another limitation is that the displacements of landmark points estimated by geometric morphometric methods are *relative*, not absolute, because of Procrustes superimposition. Consequently, it is impossible to localize which parts of a shape have changed. This issue has been exemplified by a thought problem involving the fairy-tale puppet Pinocchio, whose nose grew every time he told a lie. The only change in the shape of Pinocchio’s profile would be elongation of his nose; however, Procrustes superimposition distributes the differences across all landmarks because of the centering and minimization components of its algorithm. Geometric morphometrics can accurately recover the fact that the relationship between the nose and the rest of the head changed, but it would not be able to distinguish between growth of the nose, shrinking of the head, or an intermediate combination of the two. Alternative methods like Euclidean distance matrix analysis (EDMA), which is similar to the truss analysis described above, have been developed

specifically to localize which parts of a shape are changing.

Applications in anthropology and archaeology

Geometric morphometrics have been applied to many problems in anthropology and archaeology. The techniques are heavily used in evolutionary paleoanthropology, where they have been used to test for shape differences between putative hominin species, to statistically test hypotheses about functional relationships between morphology and factors like diet or sex, and to reconstruct ancestral morphologies using tip taxa and phylogenetic trees. Geometric morphometrics have also been applied to human-produced objects such as stone tools and floor-plan configurations of structures such as fortification towers and tipi rings, as well as to objects as varied as geographic topography and footprint outlines.

Future directions

The ease with which three-dimensional data can be obtained with laser scanners, computed tomography (CT) scanners, magnetic resonance imaging (MRI), and Lidar, have increased the demand for geometric morphometric analyses of fully three-dimensional surfaces. At the same time, they have exposed the shortcomings imposed by the requirement that all objects in a geometric morphometric analysis must have the same number of points in the same topographical configuration. Only a few algorithms exist for placing semilandmarks on three-dimensional surfaces and all of them are expensive in terms of the work and computational power required to implement them. The greatest advances in geometric morphometrics over the next decade are likely to be in automated algorithms that match surfaces and apply point grids. Some recent advances even suggest the demise of geometric morphometrics as we know it, in favor of strategies that map surfaces onto one another using pure mathematical functions instead of landmark points.

SEE ALSO: Analysis of Variance and Covariance; Cluster Analysis; Craniometry; Dental Metrics; Human Skeletal Data Quantification; Inferential Statistics; Three-Dimensional (3D) Facial Reconstruction; Lithics Data Quantification

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Human Populations

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A population is a bounded group of individuals, defined biologically by their elevated probability of mating with members of their own population and, in most cases, defined culturally by their shared linguistic, social, and historical experiences. In human populations, biological and cultural parameters are closely intertwined—for example, social concepts of ancestry and kinship often condition mating opportunities, and economic circumstances influence decisions about migration and reproduction. Each individual in a population has their own distinct life history, and this gives rise to variation among the members of the population in the extent and timing of their participation in population processes and events such as birth, reproduction, and mortality. Nonetheless, the population as a whole can be characterized by parameters that together determine population structure and dynamics (change through time). These parameters are age- and sex-structured and capture rates of fertility, mortality, and migration. In some instances, these parameters are relatively invariant through time, at least at the scale of the whole population, leading to the establishment of a stable population structure. In other instances, heterogeneity in space and time are observed, for example during colonization processes and during mortality crises precipitated by epidemic disease, natural disasters, or conflict. Populations also exhibit the long-lasting effects of previous demographic events; for example, recent episodes of population expansion can result in a star-like pattern of haplogroup clusters in genetic data.

A key question in demography is whether historical and ancient populations were fundamentally different from the populations of the present-day. Historically recent changes in nutrition, hygiene, medical treatment, and fertility

control have resulted in major transformations of the fertility and mortality experience of many modern westernized populations. The “demographic transition” refers to a repeatedly observed pattern of demographic change in which populations, typically over a period of a few generations, move from a state of high fertility and high mortality to one of low fertility and low mortality, with consequent increases in average life expectancy at birth (Kirk 1996). Although there are often marked differences between ancient and modern populations in their fertility and mortality experience, some life-history variables, such as lifespan (maximum longevity) and the ages of onset of anatomical and physiological senility, show little change from the earliest periods of history to the presentday (Chamberlain 2006). An important assumption in modeling ancient populations is that some of the properties of presentday populations, including those of ethnographically censused foraging and subsistence farming communities, can be expected to have been a feature of past populations as well.

Ancient populations were responsible for generating a range of durable material residues that can be retrieved from the archaeological record, including the skeletal remains of deceased individuals, the remains of houses, settlements, and modified landscapes, and assemblages of artifacts and other materials that accumulate during resource usage. This means that a variety of different kinds of archaeological data can be used as proxies for individuals and communities in order to reconstruct the size and structure of past populations. Mortality profiles can be estimated from human skeletal remains, and this information can be combined with the duration of cemetery usage to estimate the size of the living “contributing” population (see PALEODEMOGRAPHY). House floor areas, the spatial extents of settlements, and the productivity of site catchment areas can all be used as independent variables in formulas for estimating population sizes, although it should be noted that there is considerable variation in the spatial density of human settlements. For a given mode of subsistence, the level of consumption

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of resources can be estimated indirectly from quantities of deposited food residues, counts of artifacts, and other measures of production and usage (Schacht 1981). Demographic temporal frequency analysis uses radiometrically dated instances of human activity as a measure of the magnitude of human occupation through time (Williams 2012), and this technique has been applied extensively using summed calibrated date probability distributions to investigate regional and continental-scale changes in population size (see Goldberg, Mychajliw, and Hadly 2016 for a recent example).

Genetic evidence (see DNA: MITOCHONDRIAL; DNA: NEXT GENERATION SEQUENCING; GENETICS: ANCIENT; and GENOMICS: ANCIENT) from both modern and ancient DNA sequences provides important information about past population events including migration, colonization, and episodes of population growth and decline. Recent rapid population growth may result in a narrow distribution of pairwise differences between the DNA sequences of individuals, with their lineages clustering in star-like topologies originating from a common ancestral sequence. Comparisons of variation in sex-specific DNA haplogroups can reveal sex differences in migration rates, while measures of genetic diversity can be used to investigate variations in effective population size.

Mathematical population models are used to analyze the effects of variation in mortality and fertility on population structure and to predict patterns of population growth and decline. The effects of age-specific variation in mortality can be modeled using survival analysis, either using discrete age categories in a life table (see LIFE TABLE ANALYSIS) or by fitting mortality to a continuous

function of age as a hazard function (see PALEODEMOGRAPHY AND HAZARDS ANALYSIS). The Leslie matrix is a discrete age-structured model incorporating both fertility and mortality that can be used to predict population growth and changes in population structure. Agent-based models can also be used to explore the effects of mating rules and resource distributions on population dynamics and are a useful tool for exploring the effects of individual behavior on population-level outcomes.

SEE ALSO: Bioarchaeology; Biological Distance

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Human Skeletal Data Quantification

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Because human skeletal data ultimately involve some form of counting or measuring, they are inherently quantitative. This entry is concerned with the various ways in which scholars and researchers quantify skeletal data. In some cases, these data are quantified as simple counts for binary variables such as male versus female, presence versus absence of discrete traits (see DISCRETE TRAITS), or under versus over age 30 years for those who die above age five years (Buikstra, Konigsberg, and Bullington 1986). In other cases, data are given as counts within ordered classes, such as the number of skeletons within each age class for a life table (see LIFE TABLE ANALYSIS) or the number of skeletons that fall within ranked severities of paleopathologies. Some categorical data have no inherent ordering, for example, counts of numbers of crania within different classes of cranial shaping (see CRANIAL SHAPING) or fronto-occipital, annular, and lamboid flattening. Though one can argue that there are rankings of amount of cranial shaping within each category, the three categories themselves are unordered.

As stated above, for categorical data the quantification is given as counts within categories. How those counts are analyzed depends on the nature of the data as well as on the possible relationships of the categorical data to other variables. For example, in a life table, which consists of ordered age classes, one would typically use the counts to estimate survivorship or age-specific probabilities of death. For counts within cranial shaping categories, compositional data analysis (see COMPOSITIONAL DATA ANALYSIS) would be appropriate. For multiple categorical variables, a simple listing of counts within classes for each variable is insufficient if the variables are not independent. For example, if cribra orbitalia, porotic hyperostosis, and sex are scored as binary

variables, the counts should be presented in a 2-by-2-by-2 table. This is because cribra orbitalia and porotic hyperostosis are both considered to be skeletal markers related to anemia (see ANEMIA), while the sex of an individual is generally not independent of the risk of developing anemia. If there is no interaction among these variables, then the various margins of a cross-classification can be analyzed separately. This is because the marginal counts can always be obtained from the cross-classification. But conversely, a cross-classification cannot be reconstructed from marginal counts. Similarly, counts in “collapsed scorings” are much less useful than counts in the original scoring because the latter cannot be reconstructed from the former (Konigsberg, Frankenberg, and Liversidge 2016).

When the data from a single classificatory variable are considered against a continuous variable it is not possible to summarize the data using counts. Instead, researchers will need access to the raw data if they wish to make their own analyses. For example, in “transition analysis” (see ESTIMATING ADULT AGE: TRANSITION ANALYSIS) for estimating adult ages, one first needs to do a quantal analysis, such as probit or logit analysis (see QUANTUM ANALYSIS), to find the parameters for the transition model. If ages are in yearly categories, counts in a cross-classification of stages against age are sufficient summary of the data to estimate the transition parameters. But if age is given in decimal years (as it should be for a documented collection with birth and death dates), then researchers will need access to the raw data on stages and ages if they wish to make the analyses themselves.

If human skeletal data originate from a continuous variable, quantification can proceed by presenting summary descriptive statistics (see DESCRIPTIVE STATISTICS) for parametric analyses. These summary statistics should be given in a scale that is appropriate for the data. For example, if the data follow a normal distribution, then the mean and variance in the raw scale as well as the sample size give a complete description of the data for further analysis. In this case, there are three summary statistics. If the data are

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instead log-normally distributed, then the mean and variance should be given in the logarithmic scale. Again, this will amount to presenting three summary statistics. But if more complicated distributional forms are necessary, there will be more requisite summary statistics. For example, if the data can only be fit by a skew exponential power distribution (DiCiccio and Monti 2004), then five summary statistics are necessary, these being the location (mean), scale (standard deviation), two shape parameters, and the sample size. Assuming that the individual variables are normally distributed and that jointly they are multivariate normally distributed, the requisite summary statistics are the vector of means, the triangular part of the variance–covariance matrix, and the sample size. The triangular part of the variance–covariance matrix is the main diagonal, containing the variances, and all of the unique covariances above (or equivalently below) the main diagonal. For p variables this amounts to $p(p-1)/2$ parameters, which together with the p means and the sample size makes $(p^2+3p+2)/2$. Unfortunately, there is a long history in biological anthropology of publishing tables of sample sizes, means, and standard deviations while ignoring covariances or correlations. Konigsberg (1991) noted in regard to publishing complete summary statistics that failure to do so limited future researchers from reanalyzing data. In this era of making raw data available for download, the necessity for publishing summary descriptive statistics is potentially lessened. With that said, if neither raw data nor the requisite summary descriptive statistics are available, then publications become static references not necessarily amenable to reanalysis and further insights.

When there is further structure to the data, the number of necessary summary descriptive statistics will grow. For example, in a biological distance analysis (see BIOLOGICAL DISTANCE) between two groups, one will need the sample sizes for both groups and the vectors of means for both groups. Ordinarily, one can assume that the pooled within-group variance–covariance matrix is a reasonable representation for both groups, so that only the triangular part of one variance–covariance matrix is necessary. However, if one provides the triangular part of the variance–covariance matrix for each group, then the pooled matrix can be calculated. If only the

pooled matrix is provided, there is no going back to the original within-group matrices.

Any of the traditional univariate and multivariate statistical approaches, such as analysis of variance and covariance (see ANALYSIS OF VARIANCE AND COVARIANCE), factor analysis (see FACTOR ANALYSIS), linear models (see LINEAR MODELS), and principal component analysis (see PRINCIPAL COMPONENT ANALYSIS), can proceed from summary descriptive statistics, but in the case of specialized analyses such as those related to cross-sectional geometry (see CROSS-SECTIONAL GEOMETRY) or geometric morphometrics (see GEOMETRIC MORPHOMETRICS) the summary of data becomes more complicated. The complication arises because of the fact that geometry is involved in both forms of analysis. For the analysis of cross-sectional geometry of bones the raw data usually come as graphics image files. These can be reduced to black and white, typically with the bone in white. This reduces file size, but further reduction can be achieved using edge detection to record the pixel numbers for boundaries. Even these data are excessive and can be reduced by extracting elliptic Fourier coefficients. Elliptic Fourier reduces the perimeters to a series of harmonics that represent ellipses. Each harmonic consists of four coefficients and there are also two terms to represent the translation from the original coordinates to the center of the ellipses at 0,0. These coefficients can be used to draw the original perimeters. Because ten harmonics are usually adequate to capture the form, there are 42 coefficients to represent the outer perimeter of the bone and 42 to represent the inner perimeter. This is a substantial reduction from having to list every pixel in the traces.

In geometric morphometry the raw data consist of point locations in two or three dimensions. The data could be, for example, digitization of cranial landmarks in a craniometry (see CRANIOMETRY) study. Such digitizations are often referred to as “archiving the form” because one can extract traditional caliper-based measurements (as inter-landmark distances), but one can also analyze the landmark data directly as well as plot the average form. From the standpoint of “archiving form,” it is unfortunate that standards for data collection in advance of repatriation (see REPATRIATION) of human skeletal remains

were promulgated at a time when geometric morphometric methods were not widely available. If raw landmark data are available, then the most concise way to present summary descriptive statistics for this form of data follows from what is known as a generalized Procrustes analysis (Zelditch, Swiderski, and Sheets 2012). In such an analysis each form is translated so that its center is at the origin, it is scaled so that all forms have the same size, and then they are rotated so that the sum of squared distances between each landmark and the average landmark across forms is minimized. After this shape analysis each form can be scaled back to its original size. The average form is then literally the average landmark coordinates across the forms, while variation in landmark positions is expressed in the variance-covariance matrix of what are known as Procrustes residuals. The sum of these squared residuals across all forms and the sample size are the two final summary descriptive statistics. If k is the number of landmarks and m the dimensionality (either two for 2D or three for 3D), then the number of summary descriptive statistics is $km + km(km-1)/2 + 2$, where there are km means, $km(km-1)$ variances and unique covariances, with the sum of squared residuals and the sample size as the last two statistics. For example, ten landmarks in three dimensions for any number of crania can be described using 467 numbers.

Ultimately, researchers must make a decision whether to provide their raw data or whether to only provide summary statistics. With the increasing use of digital raw data archives, the

possibility for making such data available to others is a very real possibility. Indeed, most granting agencies now require a “data access plan” to cover the eventuality of public access to data. In the absence of such plans, researchers do need to minimally make the summary statistics available in useable form. There are unfortunately far too many publications from human skeletal biology that use and analyze multivariate data while only providing univariate summaries for the constituent variables.

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Hypothesis Testing

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Although part of the physical sciences for more than 200 years, hypothesis testing in archaeology is a relatively recent development. It arose in the 1960s, as a reaction to the limitations of the culture history paradigm that had dominated the field since its inception as a formal discipline in the late nineteenth century. In the United States, culture history was derived from the influential culture area studies of anthropologist Alfred Kroeber and others, and was a largely descriptive, inductive, pattern-searching approach, based on supposedly diagnostic artifacts (pottery types, projectile points, etc.) restricted in their time-space distributions to particular cultures thought to be analogous to those studied by ethnographers. Autochthonous development or culture contact was invoked to explain pattern changes in a conceptual framework in which induction constituted the only form of explanation. With the recognition that these archaeological cultures were constructs imposed on data by archaeologists, rather than demonstrably present in the past, and that limitations to an understanding of culture process were not inherent in the nature of archaeological data (as had often been claimed), but were instead due to flawed research designs and methodological naiveté, archaeologists began to look for ways to make the discipline more “science-like” and to strengthen our explanations of past behavior. This effort was largely confined to the Anglophone research traditions and was spear-headed by Lewis Binford (e.g., 1965) and Kent Flannery (e.g., 1973) in the United States and by David Clarke (e.g., 1968) in the United Kingdom. Binford is usually credited with the contention that, at least in theory, the entire cultural system was preserved in the archaeological record if only we are ingenious enough to decode

it. This in turn expanded the realm of archaeological enquiry enormously and generated much enthusiasm, particularly among younger scholars anxious to break with the culture history approach. It was in this context that hypothesis testing first arose.

Broadly defined, most hypotheses are conditional statements of relationship between two or more variables that have empirical referents. Statistical hypotheses come in mutually exclusive contrasting pairs referred to as the null (H_0) and alternative (H_1) hypotheses. The null hypothesis is typically the hypothesis of no relationship between/among the variables of interest and is constructed to be rejected. The alternative hypothesis predicates that a relationship does in fact exist between those variables. We are usually interested in demonstrating the existence of that relationship, *by seeking to reject H_0* with a specified probability of rejecting it when H_0 is true. There are two ways a correct decision can be made and two ways in which errors can occur. If H_0 is true for the population from which the sample is derived and H_0 is not rejected on the basis of an analysis of that sample, then a correct decision has been made. If H_0 is false for the population and is in fact rejected on the basis of the evaluation of the sample, then, again, a correct decision has been made. If, on the other hand, H_0 is really true for the population and is in fact rejected based on an analysis of a sample, then an error is made. And, if H_0 is false for the population and is not rejected on the basis of an evaluation of the sample, then an error of another kind is made. These two kinds of errors are called Type I and Type II errors. A Type I error occurs when H_0 is true but is rejected; a Type II error occurs when H_0 is false but is not rejected. The probability of Type I error is specified beforehand by the researcher and is called the level of significance (α , usually) of the statistical test. When the null and alternative hypotheses are mutually exclusive and exhaustive, to reject H_0 logically implies or entails acceptance of H_1 .

In archaeology, hypotheses are not evaluated directly but are instead evaluated in terms of their empirical referents, or test implications (i.e.,

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what we would expect to find “in the ground” if H_1 is supported empirically). In most statistical applications that involve hypothesis testing, archaeological data are considered to be samples drawn from theoretical populations whose characteristics are typically unknown. Although often ignored in practice, this fact limits the utility of hypothesis testing approaches based on parametric statistics (i.e., those that make assumptions about the defining properties of the population distribution from which the sample is drawn).

The main features of a research protocol that could be argued to characterize much quantified archaeological research regardless of the scale or nature of any particular research problem are given in Figure 1a. Sometimes called a “confirmatory mode of analysis” (CDA), it assumes that the generation of hypotheses and their evaluation in probabilistic terms is foundational in the conduct of all scientific inquiry. While clearly not the only analytical format, it is well represented in the work of contemporary professionals and it operates independently of any particular theoretical orientation.

Hypothesis testing in archaeology usually consists of seven steps that specify how one goes from (1) a general proposition of anthropological interest, to (2) an hypothesis that is meaningful in behavioral terms, to (3) propositions amenable to statistical analysis with empirical data, to (4) a procedure that defines those data, how they are to be acquired and manipulated, and in which decision-making criteria are made explicit, to (5) data collection, followed by (6) a statistical test, and (7) a reassessment of the behavioral implications of that test.

Armed with “background knowledge,” hypothesis testing begins with questions of interest to the investigator and is likely to be relevant to more tightly focused research objectives (Figure 1a, boxes 1, 2). At this stage, the investigator evaluates plausible solutions in an informal way, usually within the confines of habitual frames of reference. Many false starts are made. This exercise sometimes culminates in the development of a behavioral hypothesis (Figure 1a, box 3). A behavioral hypothesis can be viewed as a trial formulation derived from the complex factors just noted (i.e., general knowledge, background research, insight, intuition) that the investigator believes likely to express a significant

relationship between two or more variables. An explicit research design is then formulated. It tells us how to define the behavioral hypothesis empirically, what data are required to evaluate its credibility, and, often, the statistical requirements for making that evaluation (Figure 1a, box 4). The variables incorporated in a behavioral hypothesis must have phenomenological referents (test implications) (Figure 1a, box 5). In other words, they must be observable in, or recoverable from, the archaeological record and they must bear a logical relationship to the hypothesis. If they do not, there is no mechanism through which the plausibility of the hypothesis can be assessed.

At this juncture an appropriate statistical model is selected (Figure 1a, box 6). In standard CDA, the statistical model comprises the set of assumptions about the underlying properties of the population from which the sample is drawn. The relationship between the common probability distributions and the level of scaling characteristic of measurement (i.e., nominal, ordinal, interval, ratio) should be taken into account because these factors ultimately influence the choice of a test statistic. Many multivariate methods (e.g., multiple regression, analysis of variance) assume a univariate or multivariate normal distribution, equality of variance, and interval or ratio scaling. *Up to this point, no data have actually been collected* (Figure 1a, box 7). When data are acquired that meet the above constraints, they are analyzed (Figure 1a, box 8)—hopefully in accord with those constraints—and the statistical hypothesis is evaluated (Figure 1a, box 9). At this point the investigator might discover data insufficiencies, in which case, s/he returns to data acquisition (Figure 1a, box 7) and the process is repeated. If the data are determined to be adequate, a test is conducted, and the null hypothesis (H_0) is either rejected or not rejected based on the probability of Type I error specified beforehand. The result is then integrated into the broader research question from which the hypothesis is derived (Figure 1a, boxes 10, 11). Confirmatory data analysis is widely used in the physical sciences where population characteristics are known and tightly controlled experimental research protocols are the norm. So far as archaeology is concerned, a drawback to CDA is that archaeological data seldom exhibit a normal distribution or equality of variance.

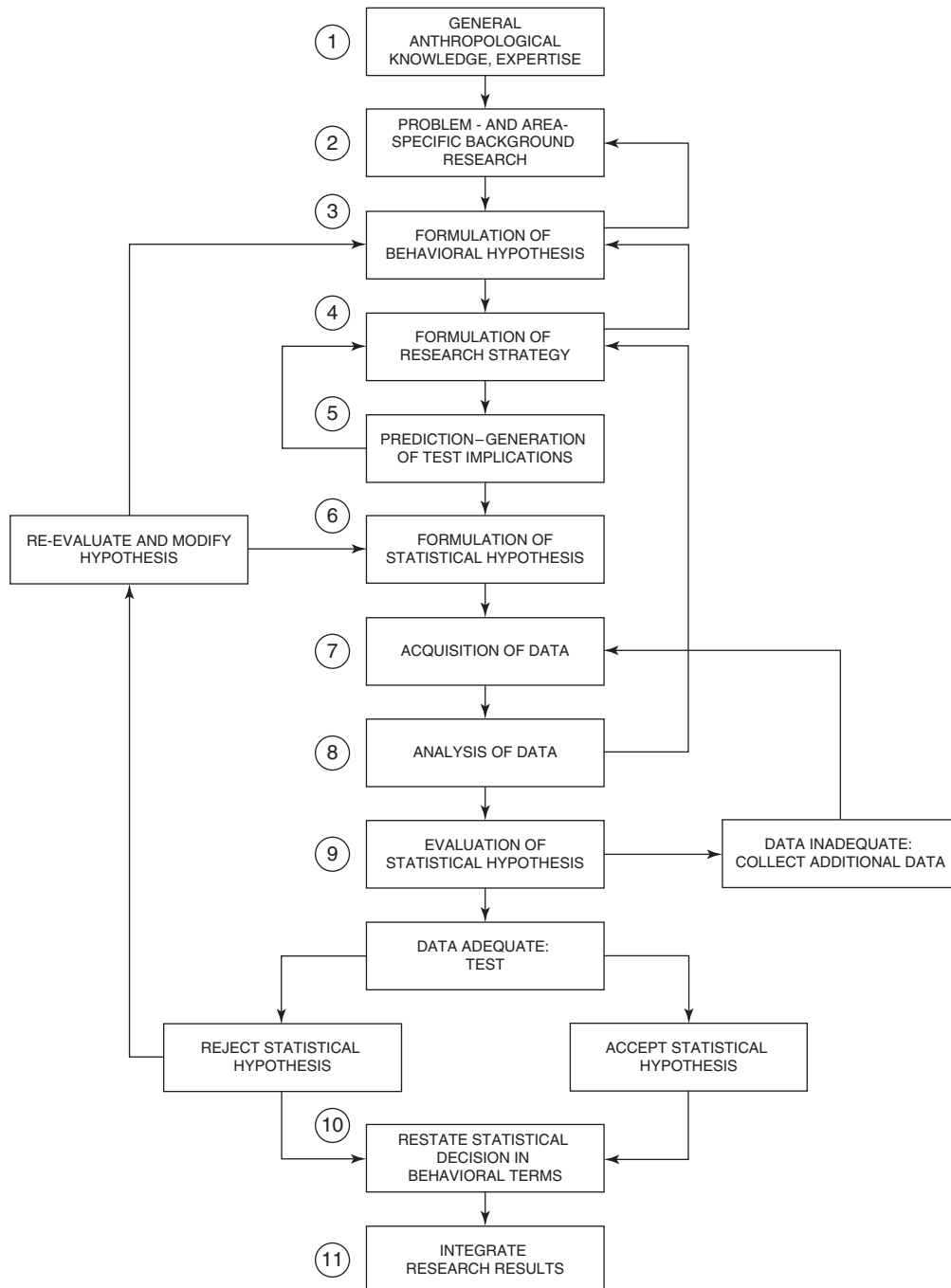


Figure 1a Hypothesis testing in a confirmatory mode. Flowchart identifies 11 stages in a generalized procedure for evaluation of research propositions.
Source: Modified from Clark 1982, 233, published by Academic Press.

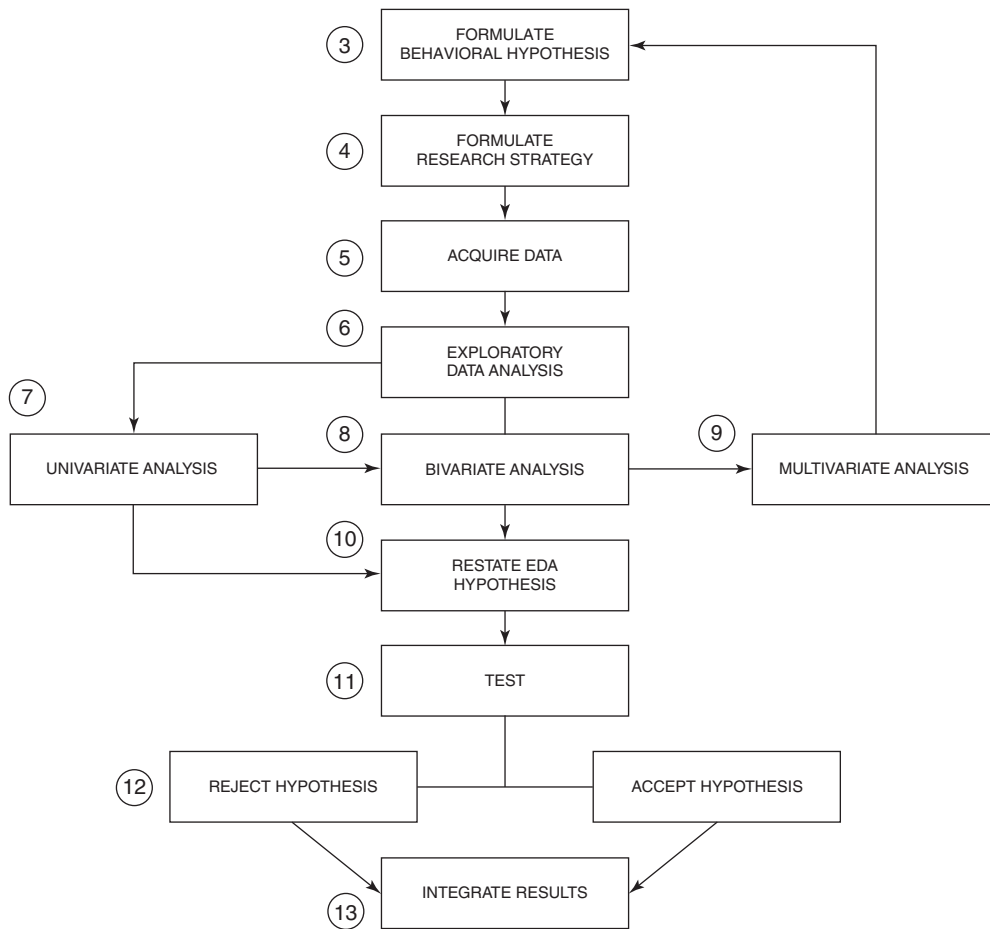


Figure 1b Flowchart incorporating an EDA pattern search in CDA mode for hypothesis testing.

Because archaeological data are often incomplete and do not meet the above constraints, a strong case can be made for adoption of nonparametric statistics. Nonparametric statistics are not based on parameterized families of probability distributions. Unlike parametric statistics, they make no (or few) assumptions about the probability distributions of the variables being assessed. To overstate the case somewhat for comparative purposes, nonparametric tests produce conclusions of the form: “Almost regardless of the shape of the underlying population distribution, we can conclude that . . .” In archaeological contexts “the shape of the underlying population distribution” is practically always unknown (in fact, unknowable). Like their

parametric counterparts, nonparametric statistics include both inferential and descriptive methods. Although hypothesis testing is emphasized here, nonparametric methods are also appropriate for a wide range of descriptive statistics including point estimation, measures of correlation, establishing confidence intervals, and multiple comparisons of rank-order data. Ranked data are common in many archaeological applications. The term refers to the ordinal level of scaling required for valid application. Examples include the Kolmogorov–Smirnov k -sample test, the Mann–Whitney U test, and Kruskal–Wallis one-way ANOVA. Some nonparametric statistics can be used when only nominal (classificatory)

scaling is present (e.g., the binomial test, Fisher exact probability test, k -sample χ^2 test).

Two other families of statistics, sometimes used in conjunction with one another, are directly relevant to hypothesis testing. They are exploratory data analysis (EDA) and a particular kind of simulation called agent-based modeling (ABM). Exploratory data analysis first developed in the late 1970s in response to dissatisfaction with the rigid numerical summaries that structure CDA. An empirical approach founded on the notion that as much as possible should be learned about structure in data *before* they are used to evaluate hypotheses, EDA complements, rather than replaces, hypothesis testing. Its most fundamental tenet is that all data are comprised of two components: the “smooth” and the “rough.” The smooth is the underlying simplified structure of a set of observations—the general shape of a distribution summarized in parametric statistics by the standard measures of location and spread (e.g., means, standard deviations). The rough consists of the residuals—what is left behind after the smooth has been extracted. What distinguishes EDA from CDA is a willingness to explore alternative models of relationship by the successive extraction of the smooth until nothing but unpatterned residuals remain. In a complete EDA scenario, analysis proceeds from the examination of single variables, to the bivariate case, and finally to multivariate analysis. The rationale behind this incremental approach is to understand as much as possible of the structure of each variable as an entity, to understand pairs of variables as relationships, and to understand groups of variables as models. Each step in the process is accompanied by a set of basic concepts and techniques that mirror their parametric counterparts (but *sans* the assumptions) and that emphasize visual displays of shape, location, and spread (the univariate case), strength and direction (the bivariate case), and residuals (the multivariate case).

It is interesting to note that, although EDA tends to suggest rather than confirm hypotheses, it is not incompatible with a confirmatory mode of analysis. One form such a “hybrid” research design might take is shown schematically in Figure 1b. The diagram is a partial expansion and reordering of some of the elements in Figure 1a. It differs from Figure 1a in three respects. First, data

are defined by a statistical hypothesis in a confirmatory mode of analysis. In EDA, data are defined directly from the behavioral hypothesis. Second, although the complete EDA scenario calls for a progression from univariate to multivariate analysis, in many archaeological applications only part of the procedure will be fully utilized (Figure 1b, boxes 7–9). Third, the behavioral hypothesis is restated in EDA terms (Figure 1b, box 10), evaluated directly (Figure 1b, box 11), and the decision to accept or reject it is integrated into the broader research questions that frame the hypothesis (Figure 1b, box 12).

While there is consensus that EDA can play an important role in hypothesis formulation, there is some divergence of opinion as to what role EDA should play in hypothesis testing. Some have suggested that EDA forfeits the right to evaluate the statistical significance of research conclusions, since they are not based on formal, *a priori* statistical hypotheses (i.e., EDA hypotheses are derived directly from sample data, and therefore to test for significance using those data would be meaningless) (Hartwig and Dearing 1979). Others claim that because EDA hypotheses can sometimes “map onto” nonparametric probability distributions, significance testing remains a possibility. Despite its research potential, archaeologists were slow to adopt EDA. It only became common in the literature in the 1990s, possibly because it is described in terms of an unfamiliar vocabulary likely to have been a considerable obstacle to graduate students exposed only to finite mathematics and nonparametric methods.

The second approach, agent-based modeling (ABM), has gained traction since 2007 because of the realization that *all* societies are complex adaptive systems (CAS) regardless of size or organizational structure (i.e., that “complexity” is not confined to “states”), are dynamic in space and time, and are fluid in membership and in how information is transmitted and processed, and that it is these multilevel, multiscale interactions that allow societies to adjust to changing internal (biosocial) and external (biophysical) conditions. Societies are seen as emergent phenomena created and transformed by the actions of individuals who “ascribe to a common body of knowledge but who make decisions contingent on the practices of other actors and the structure of social

interactions, as well as the biophysical characteristics of their environment” (Barton 2014, 309). CAS advocates maintain that the descriptive and inferential statistics that dominate quantitative archaeology today are ill-suited to deal with these complex, multilevel interactions which can only be “captured” by simulations. Although archaeological applications go back to the 1970s, they are very rare and have not before now been situated in a relatively coherent conceptual framework.

ABM can best be viewed as an experimental laboratory in which to explore nonlinear causality in complex systems and generate test implications that can be evaluated empirically against the archaeological record. It works “from the bottom up” by creating multiple, discrete computational entities (agents) that behave according to specific interaction rules (algorithms) that define how those agents process information, make decisions, and take action based on those decisions. Once the agents are specified and the rules defined, they interact in a virtual environment without further intervention by the researcher, offering a useful protocol for combining anthropological knowledge of complex adaptive systems to explore patterns that otherwise would not be apparent (Barton 2014, 311).

Like EDA, ABM can be used “by itself” in either a descriptive or inferential (hypothesis testing) mode, and can also be integrated into larger and more complex research designs. Challenges to application include the fact that many questions of archaeological interest lie “just out of reach,” with test implications that require considerable ingenuity to operationalize. ABM also abounds in unfamiliar concepts and terms embedded in the CAS literature (e.g., Cowan, Pines, and Meltzer 1994) and requires a fairly steep learning curve. Perhaps its greatest potential for hypothesis testing lies in using it to model systematic, controlled, digital environments for human socioecological dynamics.

As noted, archaeology “came late” to quantitative methods and, in consequence, hypothesis testing was not an historical part of its research protocols. A comparison of the incidence of statistical applications in articles published in *American Antiquity* over the 1935–75 interval showed mostly enumeration (8–12 articles/5 years), with minimal use of basic statistics (5–12

articles) and almost no advanced methods (0–7 articles) (Clark and Stafford 1982). After 1975, statistical usage shows a sharp upswing that continues to the present, largely as a consequence of efforts to introduce a deductive component manifest in hypotheses and their test implications into its research protocols (e.g., Watson, LeBlanc, and Redman 1971). A single recent issue of *American Antiquity* (Vol. 81, No. 2, April 2016) contains applications of Simpson’s *C* (and its reciprocal), Manning’s *Q*, the correlation coefficient *C* (the nonparametric equivalent of Pearson’s *r*), discriminant functions, EDA, principal component analysis, bivariate plots, and Bayesian models, along with LiDAR, GIS, ArcGIS, GPR, NAA, and other geophysical methods, generally within a broadly defined behavioral ecology conceptual framework.

SEE ALSO: Analysis of Variance and Covariance; Archaeological Classification; Archaeology; Descriptive Statistics; Inferential Statistics; Nonparametric Statistics; Scientific Practice; Simulation Modeling

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Inferential Statistics

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Statistical inference is a scientific process whereby properties of a population are deduced from an observed sample. Here, the term population refers to a definable collection of materials or events, each associated with one or more measurable properties characterized by some variability (e.g., a certain size range might have higher or lower frequencies than others) that can be mathematically modeled as *probability distributions* defined by one or more *parameters*. The primary objective of statistical inference is thus to determine, by analyzing observed samples, which statistical model best describes the observed distribution of variables, and at the same time estimate its parameter values. Thus, statistical inference is in contrast with descriptive statistics (see DESCRIPTIVE STATISTICS), which instead looks at the properties of the observed samples alone.

The core element of statistical inference is the selection of a statistical model: an abstract conceptualization of real-world variability capable of capturing a wide range of phenomena with few assumptions. Consider, for example, a group of individuals engaging in the production of some artifacts targeting an ideal form. Most likely, many small factors, such as different skill-sets, different perceptions of the ideal form, or the idiosyncrasies of the material, will generate variations in the size and shape of the artifact. With a sufficiently large sample size, these variations often follow a bell-curve, where the majority concentrates around a central value from which the data spreads symmetrically. This distribution can be described using the *normal distribution*, a statistical model that can portray key properties of this variation with just two parameters: the *mean* (which depicts the central tendency) and the *variance* (which depicts the spread of the variation). Statistical models enable us to quantify, for a given model and a defined parameter,

the probability of observing a particular value (in the case of discrete data) or range of values (in the case of continuous data). So for example, the probability of observing a projectile point with a length between 12 and 14 cm is 0.136 for a normal distribution with a mean of 10 and a variance of 4, whilst observing a length over 16 cm would have a probability of only 0.001. The distribution defining these probabilities is called a *probability distribution*. Different parameters would indicate different probabilities of observing a given range. Thus, observing a projectile point with a length between 12 and 14 cm would have a probability of 0.021 if the mean was 8, whilst with a mean = 13 this would increase to 0.383. We can extend this concept and compute, for a set of observations $x_1, x_2, \dots, x_n$ and a parameter value θ , the probability of observing all the sample data values. This is known as the *likelihood function*, and plays a pivotal role in statistical inference, as it enables a direct link between data and model.

Considering these foundational concepts, statistical inference is generally performed using three broad paradigms: *frequentist inference*, *likelihood-based inference*, and *Bayesian inference*.

Frequentist inference is perhaps the most widely adopted paradigm within and outside archaeology. It generally consists of a two-step process. First a *null hypothesis*, a statistical model with a given parameter, is defined. Then, given sample data, we estimate the probability of finding the observed or more extreme pattern *if the null hypothesis is true*. It follows that if this probability, known as the *p-value*, is low (generally below an arbitrary threshold of 0.05), the null hypothesis is rejected. This single hypothesis testing approach is known as *Fisher's method*, and it is slightly different from *Neyman-Pearson's method*, which instead consists of choosing between a null and an alternative hypothesis. In this framework, one first defines a priori two values representing our probabilities for committing inferential errors (α , the probability of falsely rejecting a true null hypothesis; and β , the probability of failing to reject a false null hypothesis), and then using these as thresholds for defining ranges of

values for the acceptance and rejection of the null hypothesis. One of the most common problems of the frequentist inference is the misuse and misinterpretation of the p -value. This is sometimes erroneously interpreted as the probability of the null hypothesis being true, or that its value is inversely correlated to the strength of the phenomena. The p -value is instead the outcome of many factors, from the choice of the null hypothesis to the size of the sample and the strength of the phenomenon of interest (known as *effect size*). In many situations a small sample size might fail to correctly reject a false null hypothesis, whilst a large sample size might lead to an incorrect rejection of a true hypothesis. An appropriate balance between these factors can be evaluated by means of a *power analysis*, a technique that can advise the suitable sample size required for avoiding false positives and negatives. Its application in archaeology is, however, rare (but see Wolverton, Dombrosky, and Lyman 2016), partly due to the limited possibilities for designing appropriate sampling strategies in many situations.

Likelihood-based inference is centered on the idea that likelihoods can be used to compare models. From an epistemological point of view, the key difference of this approach compared with the classical frequentist one is that it entails an explicitly comparative perspective, where the ratio of the likelihood of one hypothesis over the other measures the strength of evidence for the former over the latter. One potential problem with comparing models based simply on their likelihood is that models with more parameters often tend to have higher likelihood. This is due to the problem of “over-fitting,” a process by which a statistical model describes the noise instead of the deeper structure of the observed data, weakening its predictive power and countering the law of parsimony. A more sophisticated tool, referred to as *information criteria*, overcomes this problem by penalizing models with higher number of parameters, providing a valuable tool for comparing multiple hypotheses at the same time (see Silva et al. 2015 for an archaeological example).

Bayesian inference (see BAYESIAN STATISTICS) offers a substantially different epistemological stance rooted in the notion that knowledge of model parameters can be updated by combining

prior beliefs (described as probability distributions) with newly observed data (which relationship to the model is defined through the likelihood function). This is a rather intuitive and commonly used inferential framework. For example, in provenance analysis one might choose to ignore source sites located at great distances from where an artifact has been recovered. This constitutes an informal use of a prior belief (in this case the assumed unlikelihood of long-distance sourcing); Bayesian statistics provides the mathematical tools for formalizing this kind of inferential process. In archaeology, its widest application is within chronometric analysis, where the combination of multiple lines of evidence (such as stratigraphic relationships) can often dramatically improve radiocarbon dating (e.g., Buck, Litton, and Smith 1992).

Bayesian inference is occasionally criticized for the inherently subjective way in which priors are defined. This, however, wrongly implies that other paradigms are not affected by subjective accounts, while in fact in many cases these are hidden in the choice of methods and data. The need to provide quantitative measures of assumptions should perhaps be viewed instead as a strength of this statistical paradigm, as it offers an increased transparency in determining the role played by subjective beliefs in the inferential process. Despite its suitability for tackling many archaeological problems, Bayesian analysis is still not as widely adopted as other paradigms. This is partly due to its mathematical intractability, which often requires the use of computer simulations. Recently this weakness has been turned into a strength, with novel simulation-based approaches such as approximate Bayesian computation, which offers a Bayesian inferential framework without the need for a likelihood function and a statistical model. This greatly expands the potential range of applications of statistical analyses, which can benefit from the flexibility of computational modeling and the mathematical rigor of statistical inference (see, e.g., Crema et al. 2014 for an archaeological example).

SEE ALSO: Bayesian Statistics; Descriptive Statistics

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Linear Models

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In statistics a *linear model* is a relationship between a dependent (response) variable, y , and one or more independent variables (predictors or explanatory variables), $x_1, x_2, \dots, x_p$, of the general form:

$$y = b_0 + b_1x_1 + b_2x_2 + \dots + b_px_p$$

where $b_0, b_1, \dots, b_p$ are the model *adjustable parameters*.

Note that *interactions*, for example, terms of the product of two or more predictors, may also be included in the model. When there is a single independent variable, the relationship between x and y may be simple linear ($y = a + bx$), quadratic ($y = a + bx + cx^2$), cubic ($y = a + bx + cx^2 + dx^3$), or, in general, a polynomial of degree p ($y = b_0 + b_1x + b_2x^2 + \dots + b_px^p$). The adjustable parameters are initially unknown and they are determined through a fitting procedure called *regression*. Depending on the nature of the response variable and the predictors, as well as the regression procedure, there are several types of linear models, which are briefly presented below. Note that conventional statistical tests such as ANOVA, MANOVA and even t -tests may also be conducted via linear models, but this application will not be discussed here.

Types of linear models

In *ordinary least squares* (OLS) fitting (model I regression), the regression model corresponds to the minimum of the sum of the squared residuals, where a *residual*, d_{ix} , is the difference between the experimental and the calculated from the model y_i value at a certain x_i or ($x_{1i}, x_{2i}, \dots, x_{pi}$) value.

Thus, the ordinary least squares criterion is:

$$d_{1x}^2 + d_{2x}^2 + \dots + d_{Nx}^2 = \min$$

with N being the number of experimental points.

The underlying assumption of this process is that measurement errors concern exclusively variable y . When both independent and dependent variables are subject to experimental errors, the OLS fitting is no more reliable. In this case, the regression procedure (model II regression) should minimize the errors in both variables. There are several ways to do this. In reduced major axis (RMA) fitting, also known as standard major axis regression, the sum that is minimized is:

$$d_{1y}d_{1x} + d_{2y}d_{2x} + \dots + d_{Ny}d_{Nx} = \min$$

where d_{iy} is the difference between the experimental and the calculated from the model x_i value at a certain y_i value.

Analysis of covariance (ANCOVA) is an extension of the previous OLS models, which, additionally to continuous predictors, includes nominal and/or ordinal independent variables. Thus, ANCOVA generates predictions at the various levels of a categorical variable, while controlling for the effects of one or more continuous variables. From a statistical point of view, ANCOVA may be considered a combination of regression analysis and ANOVA.

Generalized linear models (GLMs) extend ordinary linear regression to cases where the dependent variable comes from any exponential family distribution (i.e., normal, binomial, Poisson, etc.) and is recorded as a function of continuous and/or categorical variables. GLMs require that there is no correlation between the values of the dependent variable. If this condition is not met, *generalized estimating equations* (GEEs) should be used instead. Therefore, GEEs are a version of GLMs, applicable when there is more than one measurement per individual. For example, this is the case when bilateral asymmetry is examined.

Logistic regression is a special case of GLM, where the response variable is binary, while the

predictors can be discrete and/or continuous. However, in most cases, discrete predictors are treated as continuous variables. Note that the logistic regression model, as well as GLM with a binary response, does not predict the response variable; rather, they estimate the probability of this variable belonging to each one of its categories.

Linear models have been used to address diverse archaeological questions, which are related to prediction and/or correlation. In particular, linear models have been employed to: (1) predict the average value of a certain property for a “new” case for which only values of the predictors are measured/observed; and (2) assess the contribution of each predictor to the response variable, which, in fact, means the examination of the partial correlation between each predictor and the dependent variable, while controlling for the effect of the other predictors, that is, by excluding the effect of the other predictors. The latter case may also include the examination of *interaction effects*, that is, whether a predictor has a different effect on the response variable depending on the values of another predictor. Both these tasks may be best handled if, based on the total number of predictors, the optimum linear model is selected, that is, the simplest linear model that adequately fits the data. When a response variable is recorded as a function of several explanatory variables, the optimum linear model is usually determined as follows. Starting from the *saturated* model or from any model that includes all the predictors and several of their interactions, the non-significant predictors and interactions are removed one by one. This procedure ends when only significant predictors are left in the model. Alternatively, the statistically optimum model may be selected from the smallest standard error of estimate or the smallest Akaike information criterion. Both these criteria are measures of the relative quality of a model, that is, they assess the quality of a model relative to other models. However, at this point a methodological issue should be highlighted. When conducting tests of main effects and interactions, the *p*-values of the model coefficients are used in order to assess whether their contribution to the response variable is significant. This is a case of multiple tests performed on the same data, and a common statistical practice is to adjust the *p*-values, say

using the Holm-Bonferroni method. However, this adjustment is rarely applied in relevant studies, and this omission may yield misleading results.

Applications in archaeology

The applications of linear models in archaeology are extremely broad, covering diverse topics. For this reason, only indicative examples are given below. Most of these examples have been drawn from osteoarchaeology, although brief mention is made of other subject areas.

One of the first applications of linear models is for prediction. Simple linear models have been adopted in a number of worldwide studies to predict stature from long bone length, or body mass from femoral head diameter (see, for example, Ruff et al. 2012). Such approaches are based on the correlation that exists between the size of individual skeletal elements and overall body size. Most studies have adopted OLS models, but RMA has been assumed to provide more accurate results for extended size ranges (Ruff et al. 2012). Furthermore, polynomial regression equations have been used for the prediction of age-at-death based on tooth crown heights (Mays and Pett 2014). In addition to producing regression equations for prediction, Mays and Pett (2014) used ANCOVA in order to compare the slope of the regression lines for deciduous first and second molars and found these to be significantly different, supporting a different rate of dental wear between these teeth.

Regarding applications involving non-continuous variables, logistic regression has been employed to predict the sex of individuals based on combinations of morphological skeletal markers. In such cases the dependent variable (sex) is a binary dichotomy (male–female), whereas the predictors are characteristics recorded in an ordinal scale with the ranks of this scale representing different degrees of masculinity and femininity (Walker 2008). Such approaches provide not only a sex assessment but also the probabilities of the individual being male or female.

In addition to predictions, the examination of correlations through linear models constitutes

a promising research direction in archaeology. Such an approach is particularly useful when exploring multifactorial phenomena as it allows the simultaneous examination of multiple predictors by testing the effect of each one while controlling for the effects of the remaining variables. For instance, logistic regression has been used for the study of the expression (presence-absence) of osteoarthritis, using as predictors the age, sex, and community residence of the individuals under study (e.g., Baker and Pearson 2006). In different contexts, logistic regression has been used among others to identify the variables that allow the effective differentiation of taphonomic agents (trampling marks vs. butchery cut marks) on zooarchaeological remains (Domínguez-Rodrigo et al. 2009), or the determination of iron-making practices (bloomery vs. finery) in medieval monuments using the percentage concentration of oxides as predictors (Disser et al. 2014).

As an extension of logistic regression, GLMs and GEEs have been adopted in osteoarchaeology for the study of the variables that affect enthesal changes. Enteses are the sites of muscular attachment on the bones, and morphological changes observed on these sites have been interpreted as activity markers. However, factors such as sex, age, and body size also appear to be highly influential in the expression of enthesal changes. GLMs and GEEs offer an effective means of exploring the simultaneous impact of these variables and their interactions on enthesal changes (Nikita 2014). Similarly, these methods have been adopted in the study of paleopathological conditions with a multifactorial etiology, such as dental diseases (Gagnon and Wiesen 2013). As was the case for logistic regression, GLMs and GEEs use disease expression as a response variable, and sex, age, sample chronology, and other potentially important variables as predictors. An important advantage of GLMs and GEEs compared with logistic regression is that the response variable may be binary, ordinal, continuous, or even counts. An example concerning the latter case is provided by Browne and Wilson (2013), who used GLMs to examine the most effective model of hominin raw material procurement, with an emphasis on the impact of map resolution and path choice (straight line, least cost). In this application, different GLMs were tested,

with the number of stone tool pieces used as the dependent variable, and ten variables expressing raw material properties and environmental data used as predictors.

SEE ALSO: Analysis of Variance and Covariance; Multivariate Analysis; Poisson and Binomial Distribution; Predictive Modeling; Regression and Correlation Analysis; Statistics in Archaeology

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Lithics Data Quantification

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Lithics data quantification in archaeology includes three main approaches that focus on instrumental analysis and mathematical description and characterization of stone tool form and function. Specifically, archaeologists studying lithic technology of the past increasingly rely on methods of quantification that focus on geometric morphometrics, microwear analysis, and residue analysis.

Lithic form: geometric morphometrics (GM)

At its most basic level, determining stone tool sizes and shapes is based on measurement on ratio or two-dimensional (2D) scales (e.g., length, width, thickness). More complex mathematical documentation of stone tool shape involves a number of different geometric morphometrics (GM) techniques to produce two-dimensional (2D) and three-dimensional (3D) models that are virtual true-to-scale copies of the original tools. Borrowing from biometric studies of organism form, archaeologists have quantitatively documented the shapes of stone tools (Shott 2014) using landmarks on the original tools for geometric modeling. Methods currently being employed by archaeologists to produce these virtual models include photogrammetry, various forms of laser, structured-light, and X-ray scanning, in addition to tools like contact digitizers and those that incorporate traditional linear measurement data acquired through manual acquisition of landmarks (Shott 2014).

Photogrammetry, which relies on the calculation of stone tool measurements based on series of digital images, involves point-to-point matching of landmarks on the overlapping photographs/images taken from different angles in order to replicate the tool with a point cloud and

triangular mesh frame. The number of images and the number, locations, and proper matching of points from these multiple images will affect the quality and accuracy of the virtual reconstruction (Sumner and Riddle 2008). Other approaches to morphometrics involve 3D scanning of lithic artifacts using a variety of technologies, including 3D laser scanning, structured-light scanning, and X-ray measurement systems, that are coupled with modeling software. The equipment employed to scan the lithics includes a wide range of options, ranging from relatively inexpensive digital cameras and desktop laser scanners to much more costly laser scanning systems and micro-computed tomography (CT) scanners (Shott 2014). Laser scanners sweep the surface of the stone tool using a laser that documents thousands of surface points that are connected using a triangular mesh, somewhat like photogrammetry. Unlike photogrammetry, which requires the human selection and placement of necessary points on an imaged stone tool surface, laser or structured-light approaches (Figure 1) do all of this automatically once the level of scan definition is set by the operator. Volumetric scanners, like micro-CT, rely on X-ray transmission to mathematically document the material based on cross-sections to reproduce the stone tools accurately in three dimensions (Abel et al. 2011; Grosman, Smikt, and Smilansky 2008).

Examples of the application of these methods include the virtual reproduction of Acheulian hand axes and Levallois core and flake tools, typological classifications, and the documentation of technological details on chipped stone tools (e.g., cortex coverage, flake directionality, retouch and refit studies, and raw material texture) (Abel et al. 2011; Grosman et al. 2008; Shott 2014; Sumner and Riddle 2008). Virtual modeling may be used to produce 3D replicas of lithic artifacts from epoxy resins/plastics. Consequently, virtual documentation and quantification of stone tools have significant curatorial and exhibition benefits, as well archaeological data-sharing applications (Abel et al. 2011; Shott 2014; Sumner and Riddle 2008).

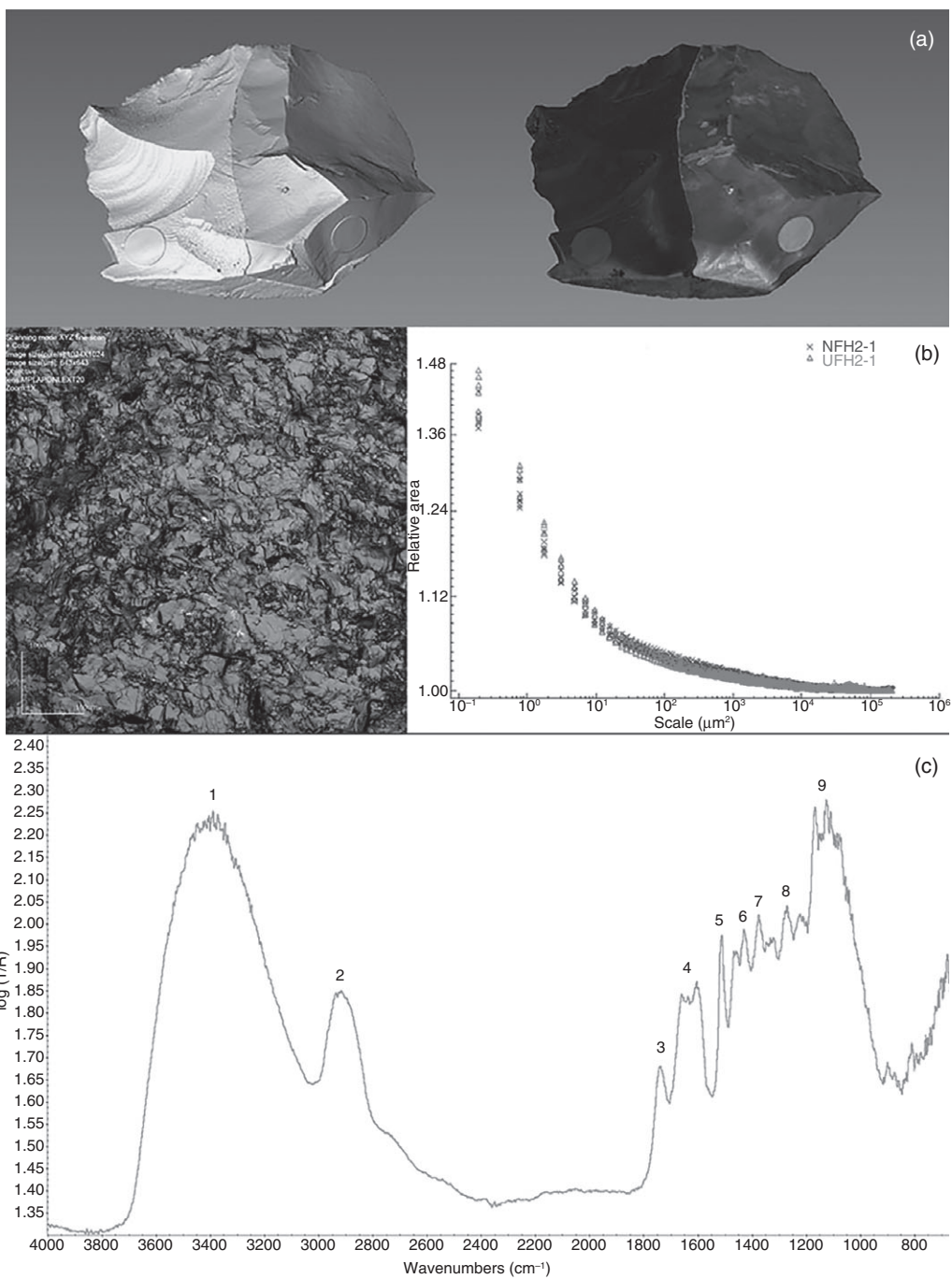


Figure 1 (a) 3D digital models (virtual augmentation—left; grayscale reproduction—right) of two refit flint flakes from the Lower Paleolithic site of Elveden, England, using a MechInnovation MechScan structured-light scanner. Source: Image provided by Adrian Evans and Rob Davis, Fragmented Heritage. (b) 2D digital image scan of the surface of a quartzite scraper used on fresh hide (FH2) taken with an Olympus LEXT OLS4000 laser scanning confocal microscope—left; graphed results of relative areas (Srel) of the unused (NFH2) and used (UFH2) surface scans on the scraper—right. Source: Image provided by the author. (c) FTIRM reflectance spectrum for wood pith residue on a flint flake gathered using a Nicolet Continuum FTIR microscope paired with a Nicolet iS50 FTIR bench presented as inverse wave numbers and calculated absorbance ($\log 1/R$, where R = reflectance). Source: Image provided by Gilliane Monnier, University of Minnesota.

Lithic function: microwear analysis

Microwear analysis relies on the observation and documentation of edge or surface alteration of stone tools resulting from use. Stone tools are examined using various types of microscopes, from low-power ($<100\times$) stereomicroscopes to high-power ($200\text{--}500\times$) metallurgical and ($>500\text{--}10,000\times$) scanning electron microscopes (SEM). Lighting of tool surfaces, typically angled or direct/reflected, permits observation of different types of wear features at different magnifications. Identification of tool use is based on the interpretation of the combination of wear features (e.g., edge microchipping, edge rounding, striations, and micropolish/abrasion) observed by the microwear analyst and the subsequent assignment of most likely function of the tool in terms of tool motion (e.g., cutting, drilling, scraping) and the contact material based on either hardness (e.g., soft, medium, hard) or more specific type (e.g., bone, hide, wood) (Stemp, Watson, and Evans 2016).

Quantification of microwear does not rely on the visual interpretation of use-wear features; it uses mathematical data derived from the stone tools' edges and surfaces to determine function. Much of the method and theory for edge and surface quantification employed by archaeologists is borrowed from the engineering fields of metrology and tribology (Evans and Macdonald 2011; Stemp et al. 2016). Early attempts at quantification of microwear included techniques using measurement of edge fractures and loading principles, as well as white light interferometry, profilometry, and different forms of digital image analysis, among others (Stemp et al. 2016). Technologies to

quantify lithic surfaces on micro- and nano-scales include atomic force microscopy (AFM), laser profilometry, interferometry, laser scanning confocal microscopy (LSCM), white light confocal microscopy (WLCM), and focus variation microscopy (FVM). These measurement systems are coupled with various software packages for the calculation of surface texture/roughness using algorithms, such as average roughness (S_a), root mean square roughness (S_q), relative area (Srel), and area-scale fractal complexity (Asfc) (Evans and Macdonald 2011; Stemp et al. 2016). In addition to the mathematical documentation of surface texture/roughness, these systems can generate 2D and 3D images of the tool surfaces, thus providing a visual complement to the quantified surface data (Figure 1b).

Most of this work is in its experimental stages, focusing on increasing understanding of wear formation processes on stone tools, the effects of post-deposition on lithic microwear, discrimination of wear resulting from contact with different worked materials, wear development and use-duration, and wear on various raw material types (e.g., flint, chert, obsidian, quartzite). However, there are applications to lithic artifacts, including Upper Paleolithic flint tools from England, Neolithic flint tribulum blades, an obsidian bracelet fragment from Neolithic Turkey, and Mousterian flint tools from Russia, to name a few (Evans and Macdonald 2011; Stemp et al. 2016).

Lithic function: residue analysis

Traditional residue analysis is based on microscopic observation and morphological

identification of the remains of animals (e.g., blood, fats, lipids, collagen, keratin), plants (e.g., starch grains, phytoliths, raphides, pollen, cellulose), or other substances (e.g., ochre, cinnabar, metals) adhering to lithic artifact surfaces. Residues may be observed and analyzed while still adhering to the stone tools or they may be extracted for later observation and analysis. As with microwear analysis, microscopes of various magnifications, lighting arrangements (i.e., reflected, transmitted), and polarizers are used for this purpose, including low-power stereomicroscopes, high-power metallurgical microscopes, and scanning electron microscopes (Monnier et al. 2013; Rots et al. 2016). Extracted residues that are degraded, fragmented, or otherwise amorphous can be identified using stains, such as Methylene Blue for cellulose or Orange G for collagen and keratin. Identification of residues can also be accomplished by using biochemical reagents, most notably for immunological reactions to suspected blood proteins, and DNA analysis (Rots et al. 2016; Stemp et al. 2016).

Quantification of residues is primarily based on the measurement of molecular compounds, minerals, and trace elements in the residues that can be used to objectively identify the substances on the surfaces of stone tools by matching them to the compositional data of known materials. Various techniques are employed for these analyses of both organic and inorganic residues, including gas chromatography mass spectrometry (GC-MS), liquid chromatography mass spectrometry (LC-MS), Fourier transform infrared spectroscopy/microscopy (FTIRM), Raman spectroscopy/microscopy, X-ray diffraction (XRD) analysis, and scanning electron microscopy with energy-dispersive X-ray spectroscopy (SEM-EDX). Each of these techniques measures residue composition differently, but identification is based on the production of a unique chemical signature (i.e., size and position of peaks of the substance sampled when graphed) (Figure 1c). These residue analysis techniques can be combined with optical microscopy to provide both visual and compositional data (Monnier et al. 2013; Prinsloo, Wadley, and Lombard 2014).

Certain residues may become adsorbed into the tools' stone matrix during the process of wear and can be detected based on the analysis of the elemental composition of lithic surfaces

themselves using techniques such as ion beam analysis (IBA), laser ablation inductively coupled plasma mass spectrometry (LA-ICP-MS), proton-induced X-ray emission spectroscopy (PIXE), and Rutherford backscattering (RBS) (Evans and Donahue 2005). This information is not only employed to determine tool function, it has also been incorporated into the debate about wear formation processes on chipped stone tools. Two main concerns when attempting to identify residues using any of the visual or quantitative techniques presented above are residue degradation and environmental/depositional or human contamination of the samples (Monnier et al. 2013; Prinsloo et al. 2014). Some archaeological and experimental examples of quantification of residues include the identification of bitumen on lithic artifacts from Syria and animal residues on tools used in hunting and butchery of blue wildebeest, among others (Monnier et al. 2013; Prinsloo et al. 2014).

Increasingly, various morphometric, microwear, and residue analysis methods based on quantification of data derived from lithics are being used by archaeologists around the world. Many of these methods are in various stages of development, with some still in early experimental phases that require further testing. Overall, results using these methods for quantification of lithic form and function are promising. Increasingly, quantitative data derived from these methods of stone tool analysis are being combined with more traditional approaches, such as photography/illustration and optical microscopy (Stemp et al. 2016), to provide more detailed information about how lithic artifacts were made and used in the past by humans and their hominin ancestors.

SEE ALSO: Archaeological Classification; Computed Tomography; Databases in Archaeology; Digital Photogrammetry; Fractal Models; Gas Chromatography–Mass Spectrometry (GC-MS); Geometric Modeling; Geometric Morphometrics; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Infrared Reflectance Spectroscopy; Ion Beam Analysis (PIXE/RBS); Laser Scanning; Nanoarchaeology; Optical Microscopy; Organic Residue Analysis; Palynology; Photogrammetry and Stereophotogrammetry; Phytolith Analysis; PIXE and

Material Analysis; Raman Spectroscopy and Material Analysis; Starch Granule Analysis; Three-Dimensional (3D) Printing and Additive Manufacturing

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Mathematics

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Mathematics underlies a number of scientific methods used in archaeology today and exercises a great influence on all survey, excavation, and recording procedures. The ambiguities and imprecisions of verbal description and narratives which characterize traditional archaeology are being substituted by mathematical language and formalized datasets preconceived for use in automated computer-based analytical processes (see COMPUTER APPLICATIONS IN ARCHAEOLOGY). These changes follow the general shift in the way that knowledge is built, shared, and communicated by the scientific community, and how it is acquired by society. Computer technology allows processing a great amount of data and rapidly performing complex mathematical operations, reinforcing the use of a wider empirical base in archaeological knowledge and enhancing an overall use of mathematics in archaeology.

Mathematics not only is a tool that can serve in archaeological research but also can be used to represent the structure of an archaeological *problem*, that is, questions raised regarding archaeological material and the past in general. An enquiry into past social realities can be expressed as a relation between causes and consequences. For example, *what differences in actions* (production, use, distribution, and so on) *are the causes of the observed variations* (size, form, composition, texture, localization, etc.)—and vice versa. Whenever we express an idea through an order relation of its components, we can express it mathematically. The subjective terms and concepts traditionally linked to expressing archaeological problems can therefore become explicit and well defined in formal terms through mathematics. Material evidence of past social action is distributed in

space and time as a consequence of causally related events. The most precise way to describe material evidence and its distribution in space and time is to apply artificial language to express observed and measured relations. The basic unit of artificial language is *quantity*. Certain entities possess “quantities” of something, for example, gradation and intensity. On the contrary, *qualities* are not equivalent to gradations and cannot be expressed in terms of order. They must be expressed as either “present” or “absent” (0–1). *Quantities* allow the ordering of objects or phenomena in terms of relations of order. Hence, if an archaeological problem is advanced as a mathematical structure with formalized datasets, then mathematics can be applied to solve it.

Nevertheless, the use of numbers or formal language to describe the archaeological record is still rare. The use of mathematics was an exception rather than a norm back in the 1970s (Orton 1980), and even today lacks support among most archaeologists. Yet advances in computer technology allowed the first early applications in archaeology in the 1960s (Doran and Hodson 1975). At that time, the success of quantitative archaeology was associated with computerization and algorithm improvements for cluster analysis, scaling techniques, “factor” analysis techniques, and multidimensional data analysis. The very idea of quantitative archaeology took a step forward between 1975 and 1990 as seen by the transition from a preliminary theoretical discussion to the application of quantitative methods to archaeological data, the diffusion of multidimensional data analysis, the development of new algorithms, and the possibility of using ready-made software. About the same time, new theoretical developments in archaeology influenced by “new archaeology” or “processual archaeology” emphasized scientific methods in archaeological research based on statistical tests, algebraic models, spatial analysis, system dynamics, linear programming, and the catastrophe theory. After 1990, the research based on quantification of archaeological data and the development of new methods decreased,

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probably due to new theoretical trends in social sciences and humanities such as, for example, post-modern paradigms and the collapse of formal rationality.

Mathematics today is embedded in software applications used in archaeology such as database management (see DATABASES IN ARCHAEOLOGY), tele-detection, geographic information systems, visualization, virtual reality (see VIRTUAL REALITY MODELING), and artificial intelligence (see ARTIFICIAL INTELLIGENCE). Computing seems to be at the center of much interest in heritage studies. “New mathematics”—chaos theory, fractals, neural networks, nonlinear systems, multi-agent systems, Bayesian statistics (see BAYESIAN STATISTICS)—is being successfully tested in archaeology, confirming the fundamental role of mathematics in the description and explanation of complex archaeological systems.

The first domain where “numbers” are used in archaeology is in data acquisition and description. The properties of size, shape and form, texture or visual appearance, and finally matter and location (the position of the object in space and time) require accurate structured and formal description. This domain is fundamental for archaeological classification (see ARCHAEOLOGICAL CLASSIFICATION), that is, ordering information for subsequent measuring, counting, and comparing. From the amount and/or differences among archaeological observables, we can measure and quantify social action. Quantity of labor, efficiency of tools, and cost/benefit ratios of hunting or herding are examples. The mathematics of similarity and inductive inferences is also relevant to

archaeology. Two objects may be “implicitly” related or connected in spite of dissimilarities. Furthermore, theory and methodologies drawn from complex network models are increasingly explored as a means of understanding dynamic social relationships in the past. Another key domain where mathematics is fundamental is chronometry, or chronological modeling. The way to reconstruct a temporal ordering and its specific metrics is of the utmost relevance in archaeology because of the temporal variation in the approach to the very idea of change and evolution.

All of the cited domains converge in one of the most powerful tools for analysis and interpretation of historical processes: computer simulation. The simulated models serve to understand archaeological observables in terms of a priori relationships between observed assets and the inferred properties/abilities of people having generated them.

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Measurement Theory

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Science has embraced evidence-based measurement as the dominant criterion for valid knowledge about the physical and social worlds. Accordingly, the theoretical foundations of measurement are a concern of scientists and philosophers. In the process, rules and assumptions have been proposed and debated as a basis for valid measurement. Measurement theory is the justifying logic behind this rule-making process (Roberts 2009; Tal 2015). This entry reviews traditional concerns and recent trends in measurement theory.

Traditional concerns of measurement theory

For much of the twentieth century, measurement was considered the assignment of numbers to properties of material and immaterial systems with the expectation that the structure of the numbers and the systems are isomorphic. Among the problems of measurement in this view are representation, error, and scale. The problem of representation is concerned with the justification of the assignment of numbers to properties of objects. A simple example is to show that the number of items in a sample is isomorphic with the set of real numbers (1, 2, 3) in an absolute numerical scale. The problem of error is concerned with accounting for the difference between actual and observed measurements. The traditional belief was that errors in measurement could be reduced by refinements in measurement theory and instrumentation.

The problem of scale concerns the scale type appropriate to a particular measurement procedure. The most commonly used scale of measurement was and remains the nominal, ordinal, interval, and ratio scale. An example

in archaeology of a nominal scale attribute (in name only) is the presence or absence of notching on a projectile point. An ordinal scale attribute (forming a sequence with no fixed distance between measures) is a ranked measure like light or heavy grinding on the point. An interval scale attribute has an arbitrary zero point but a fixed distance between measures like calendar dates for points. A ratio scale attribute is similar but has a fixed zero point, such as length and weight measures. Determining at which scale a measurement is made was considered important, for it affects the types of numerical procedures that could be applied to the resulting data.

Throughout this period, measurement theory was embedded within positivism, a strongly empirical philosophy that assumed (among other things) that: empiricist observation is the only rational means of exhibiting the laws of the social world and human mind; universals do exist for the social world and human mind; universal truths can be established through the rational application of the scientific method; observation and measurement are the core of the scientific enterprise; and observations and theoretical terms are different realms of being, with observations matters-of-fact and theoretical terms subjective (Uebel 2011, section 3). These views led to attempts like operationalism and conventionalism to coordinate observations and theoretical terms.

Recent trends in measurement theory

Although necessarily oversimplified here, the above views had a stultifying effect on archaeology and the social sciences, for notions like social systems and their change cannot be directly observed in the same manner as a rock or a tree can. The result was the labeling of social science as “soft,” its endeavor as “speculative,” and its use of measurement problematic at best. In archaeology, measurement was largely confined to characteristics of observables like artifacts using the scales mentioned above, though advances in

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technology expanded how these measurements could be made and represented.

Trends in measurement theory since the 1980s have highlighted weaknesses in traditional measurement theory. These trends redefine what observation and measurement mean, and the purpose of measurement, among other suggested redefinitions (Tal 2013; Michell 2003; Dixon-Romain and Gergen, undated). For example, because of the nature of perception and its situation within sociocultural settings, all observation, and objectivity more generally, is theory-laden; as a consequence, scientific theories are revisable and their final “proof” questionable; rather than a search for universals, interest has turned to the particularity of individual sociocultural settings; and the demonstration that the empirical tradition of measurement is at odds with the workings of the human mind has led to the investigation of what scientists actually do in practice.

The advent of model-based theories has led to the suggestion that models and simulations are in fact measurement systems themselves, even when not cast in mathematical form. These developments led in turn to the importance of coherence among the elements of these methodologies and to the problem of observational grounding, for just what is empirical and what is theoretical is in actuality blurred. Finally, social scientists have become increasingly concerned with the purpose of social science in an age of seismic changes in social life. To paraphrase Biesta (2009, 1), “should we value what we measure or measure what we value?” In archaeology, Doran (2015, v) suggests that archaeologists should be “using such access as we have to our past to guide our choice for our future as a species.”

Trends in measurement theory challenge archaeologists to be more open in their

conception of and creative use of measurement. Unleashed from the constraints of positivist views of measurement theory, archaeologists have the opportunity in the twenty-first century to greatly expand our understanding of the past and our future as human beings.

SEE ALSO: Descriptive Statistics;
Nonparametric Statistics; Statistics in
Archaeology

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Multivariate Analysis

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Multivariate analysis (MVA) encompasses the ensemble of statistical techniques that simultaneously try to expose the underlying meaning of datasets with several measured variables for each entity. Its principal objective in our discipline is to obtain a better description of the data under analysis by reducing it to a form that may be used to inspect its structure from an archaeological perspective.

These methods, consolidated within the general toolset of quantitative archaeology since the early 1980s, have proved their usefulness in plenty of archaeological case studies over the years. Nevertheless, the majority of those works have incessantly pointed out a structural problem: While mathematical training among archaeologists was, in the best-case scenario, superficial, historical reasoning made by statisticians who tried their hands at archaeology was usually no better. On the bright side, archaeologists seem to have reached a clear consensus on the importance of MVA in the discipline. Despite the lack of enthusiasm for these methods within current mainstream archaeology, their effectiveness in helping to understand complex datasets has given them a place in both university curricula and scientific journals.

A brief history of multivariate analysis in archaeology

The use of MVA in archaeology began in the mid-1960s, highly related to the general development of quantitative methods in social and human sciences. Despite a first attempt to introduce this general framework in archaeological research in the early 1950s by Oliver H. Myers, the first book dedicated to the matter was edited by Heizer and Cooke in 1960. The very idea

of quantitative archaeology was based at that time on the implementation of multidimensional matrices for data management and, therefore, the development of MVA, as regarded by Clarke and Gardin in their first works. This seminal scenario is only understandable within the context of computational development and its implementation for academic basic research. That was the breeding ground for the beginnings of a quantitative revolution in archaeology, which took place between the mid-1960s and the next decade. Some of the first applications of statistical techniques to archaeological datasets were developed through those years in the works of Hodson, Doran, Binford, and so many other pioneers.

The decade of the 1970s saw the consolidation of computer-aided systems that made possible the implementation of an increasing number of complex algorithms for multidimensional data calculations. Two main schools of MVA in archaeology were developed through that period around different leading researchers: One in the United Kingdom focused on multidimensional scaling methods, and the other one, established in France, was mainly working on several applications of correspondence analysis. Research efforts in this field during the following decade continued to highlight the potential of computerized statistical methods for solving the multivariate problems with which archaeologists deal. Among the most habitual multidimensional techniques implemented in archaeological research during those years can be highlighted the importance of correspondence, principal component, and cluster analysis. MVA case studies multiplied in a wide range of archaeological issues, from taxonomy to seriation or spatial analysis (Madsen 1988; Shennan 1988; Jones 1986). Those years are considered as the true founding era of quantification and multivariate statistics in archaeology, mainly due to the spreading of these methods worldwide.

Progress and diffusion of personal computers and specialized software during the 1990s shifted the focus of archaeological mainstream approaches onto computational methods, where geographic information system (GIS), databases,

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and technological gadgets took over. A quick *n*-gram search on the internet shows a general tendency to reduction in the use of all major MVA techniques in scientific publications during this period. It was the era, too, of profound criticisms towards the general theoretical framework of processual archaeology, trying to provoke a paradigm shift to post-modern perspectives. Some of the most important texts that tried to synthesize the Herculean amount of work developed during the previous decades were written in that context (Baxter 1994), as well as the majority of attempts to integrate quantitative methods within archaeological theory and reasoning, a recurrent topic since the early 1980s (Gardin 1979).

Despite an increasing number of computational applications in archaeology, the twenty-first century has seen the recovery of applied quantitative practices in our discipline. That scenario includes some important enhancement in MVA techniques, as well as a continuous refinement of the theoretical frames of reference for archaeological reasoning (Barceló and Bogdanovic 2015). While new quantitative methods are being assimilated from formal sciences (Bayesian statistics, neural networks, system dynamics, graph-based models, non-Euclidean statistics, etc.), the procedures destined to address multidimensional datasets have encountered new stimuli in order to improve.

For example, by analyzing the application of MVA techniques in four of the main journals within the domain of archaeological sciences (*Journal of Archaeological Science*, *Archaeometry*, *Journal of Archaeological Method and Theory*, and *Archaeological and Anthropological Sciences*) during the years 2009–2016, a sustained interest in these kinds of procedures can be observed. Even taking into consideration the effects of monographic issues in the bias of topics, each one of these journals presents several papers on multidimensional methods in each volume. It should be noted, among others, the relevance of cluster analysis in the *Journal of Archaeological Science* (>30% of the total number of papers published each year) and the continued interest in principal component analysis in *Archaeometry* (≈13% of the total number of papers published each year).

Current research applications

There exist several forms of categorization for MVA methods, depending on either their purpose (data reduction, clustering, prediction, etc.), the nature of the variables used in the analyses (dependents or independents), or the kind of data (quantitative or qualitative). Generally, the most widespread classification establishes two main categories: dependence and interdependence techniques. The first assumes the existence of both dependent and independent variables, and they are aimed at determining whether the set of independent variables affects the dependent ones and how. On the other hand, interdependence techniques do not make any assumptions about the nature of the variables or specific hypotheses and they try to analyze how they interact between them.

MVA has had a major impact on four main archaeological kinds of problems: (1) the analyses of chemical composition of artifacts; (2) typological/morphological classification; (3) assemblage comparisons; and (4) spatial analysis (Baxter 1994). Taking into account the above-mentioned classification of multidimensional procedures and, in a broad sense, these four fields of application, it is possible to highlight some examples of their use in archaeology.

Dependence techniques

Dependence techniques try to validate empirically a previously developed hypothesis, and they are considered as explanatory or predictive approaches.

- Multiple regression analysis (MRA) (see REGRESSION AND CORRELATION ANALYSIS): It is assumed that the dependent variable is quantitative. It is typically used to predict the behavior of the dependent variable as a linear function of the independent variables. Some archaeological applications of MRA procedures include: (1) osteoarchaeological prediction of the age of the specimens from several measures on their bones; (2) partition of mixed archaeological collections by estimating the best combination of specified sets of sources in the composition; and (3)

prediction of an archaeological outcome, such as the amount of archaeological material in a specific spatial demarcation, from several independent variables.

- Canonical correlation analysis (CCA): It is assumed that the dependent variables are quantitative. Its main aim is to simultaneously relate several metric dependent and independent variables, by calculating linear combinations of each variable group that maximize the correlation between them. Some archaeological applications of CCA procedures include: (1) assessment of projectile point typologies; (2) isolation of distinct toolkits associated with different kinds of cooking features; and (3) comparison between factors regarding settlement trends and yields in close fields.
- Multivariate analysis of variance (MANOVA) (see ANALYSIS OF VARIANCE AND COVARIANCE): It is assumed that dependent variables are quantitative. This statistic uses qualitative independent variables to define different groups, for which it is assumed that mean score on the dependent variables will be statistically equal for every group. It is usually used in order to quantify the strength between variables by testing the differences between underlying unobserved latent variables derived from the variables in the dataset. Some archaeological applications of MANOVA procedures include: (1) assessment of the degree of variation in *raphide* size within and between plant species for understanding ancient plant exploitation; (2) analysis of similarity between assemblages to determine what groupings make sense based on morphological features; and (3) comparison of variables within time-sliced datasets in order to characterize different historical landscapes.
- Multiple logistic regression (MLR): It is assumed that the dependent variable is qualitative and binominal. The aim of this technique is to predict the probabilities of the dependent variable or, even, to suggest the effect of the independent variables on the nominal one. It is very similar to multiple discriminant analysis, but it can be used to answer the same research questions when the rarely attainable assumptions imposed

by its counterpart cannot be fulfilled. Some archaeological applications of MLR procedures include: (1) prediction of critical level of scalar stress on the basis of community size, assessing the probability that a group reaches a hotspot of size development critical for its internal cohesion; (2) comparison of different mitochondrial lineage scenarios in population models to analyze which of them best fits the observed data; and (3) weight of independent variables as beta values for an inferential probabilistic model for settlement location.

Interdependence techniques

The main aim of interdependence techniques is to describe or reduce reality by synthesizing the most relevant information of the dataset.

- Principal component analysis (PCA) (see PRINCIPAL COMPONENT ANALYSIS): It is assumed that the dataset values are metric. Its main goal is to obtain a two- or three-dimensional picture of complex multivariate data. If archaeological data are represented by a set of points in a multidimensional Euclidean space defined by several orthogonal axes, the purpose of PCA is to find a new set of them that best fit the actual spread of the data. This technique, therefore, involves finding a new and often smaller set of uncorrelated variables (*components*) linearly related to the old set that summarizes them in an effective way. Some archaeological applications of PCA procedures include: (1) identification of groups of chemically similar artifacts that could potentially be used to answer questions of provenance; (2) evaluation of the reliability of typologies in measuring the effects of variation in lithic reduction by describing distinctive assemblages; and (3) analysis of the influence of environmental and resource proximity measurements in occupation strategies and settlement location.
- Multidimensional scaling (MDS): It is assumed that the dataset values are metric. These methods iteratively seek a good-fit solution to the general task of embedding

Euclidean coordinates in a set of similarity relations between the objects. Usually, the similarities are represented in the form of an $n \times n$ symmetrical matrix of all pairwise distances. Unlike other ordination methods, MDS makes few assumptions about the nature of the data, becoming well suited for a wide variety of cases. Neither linear nor modal relationships are assumed for the data matrix and any distance measure between data points is allowed, unlike other methods. Moreover, because MDS operates on dissimilarities, no statistical distribution assumptions are necessary. Some archaeological applications of MDS procedures include: (1) determination of associations between variables and cases of experimental data, such as physical and chemical properties of ceramic artifacts; (2) evaluation of societal developments by producing gradients for a quantitative measurement of cultural change on a linear timescale; (3) comparison and representation of the relations between archaeological sites from their material assemblages; and (4) transformation of spatial processes to pseudo-Euclidean frames of reference based on their cost distance pairwise matrices, providing more exact insights of their spatial structures, taking into account the heterogeneous surface in which they take place.

- Cluster analysis (see CLUSTER ANALYSIS): The dataset values can be both metric and non-metric. This is a method for ranking entities in a small number of groups in such a way that similar subjects are placed in the same group. Cluster analysis is a useful starting point for other purposes, such as data summarization. Whether for understanding or utility, cluster analysis has long played an important role in a wide variety of archaeological analyses. Hierarchical agglomerative and partitioning procedures are among the most habitual approaches to this kind of analysis, but new scenarios, such as model-based clustering and fuzzy clustering, are growing in importance. The outcome from a clustering of a dataset may have little meaning, since the resulting clusters are not associated with any concept arising from the domain of study, but only from the inherent structure of the data. Some

archaeological applications of cluster analysis procedures include: (1) unsupervised ranking of archaeological artifacts by using their compositional data for creating homogeneous clusters; (2) creation of artifact typologies arising from different measurements of the entities composing the dataset; and (3) identification of patterns in point scatters at both the intrasite and intersite level.

- Correspondence analysis (CA) (see CORRESPONDENCE ANALYSIS): It is assumed that the dataset values are nonmetric. CA is a statistical exploratory tool whose popularity has steadily grown in the social sciences as well as in archaeology. It graphically represents the dependence between rows and columns of contingency tables. The visual display of data helps the interpretation and allows patterns to emerge. The technique reduces the number of dimensions needed to display the data points by decomposing the total inertia (i.e., the variability) of the table and defining the smallest number of dimensions capable to capture the data variability. Some archaeological applications of CA procedures include: (1) stratigraphy and formation processes, seriation, and chronology; (2) comparison of artifact assemblages; and (3) analysis of intrasite activity areas.

Future perspectives

As previously stated, MVA tries to reduce complex datasets into a form in which to obtain a better description of the data under analysis. This objective includes both analyzing relationships between measured variables and categorizing the ensemble of entities within the dataset into coherent classes. Nevertheless, archaeological data tend to be more complex than the inductive models that emerge from reduction analyses. Recent works have tried to deal with this problem by presenting several nonlinear forms of classification (Barceló and Bogdanovic 2015).

Those works emphasize the importance of a deductive framework, in which both conceptualize the classifications archaeologists are dealing with and reveal the inherent structure present within the data. While several forms of data

reduction are still solid tools for exploratory analysis, current trends in MVA are trying to develop more refined forms of supervised classification. Several limitations in available methods like clustering or discriminant analysis have been recently pointed out in that sense, highlighting other possible alternatives. An important step forward in the general framework of multidimensional applications can be shown with the introduction of *immersions* in pseudo-Euclidean spaces. These allow us to apply properly any multivariate method to analyze projected data that fits better the archaeological structure represented, in both compositional and spatial analysis problems.

Besides refinement of MVA techniques, other approaches to the same kind of multidimensional datasets are now breaking new ground, mainly in relation to fuzzy classifications and neural networks. The former approach assumes intermediate values for statements between true and false, and besides reflecting closer the archaeological reality, it also provides a method to quantify qualitative matters in terms of reliability or confidence. Entities in the dataset are assigned to different classes with indexes that reflect the probability of the assignment of each item to a typological class, as a form of uncertainty estimation (Nicolucci and Hermon 2015). Closely related to this topic is the neural network approach (see NEURAL NETWORKS), which can be used as a nonlinear fitting mechanism to find compositional regularities in a set of experimental data (Baxter 2006). This procedure learns by sequentially applying input vectors, while adjusting network weights according to a predetermined procedure. In this way, once trained, the network identifies any input pattern and tries to output the associate scheme previously learned, offering the possibility to understand complex and incomplete archaeological datasets. Relating MVA and new forms of semantic relationships beyond resemblance are encouraging the development of both this methodological field and archaeological reasoning.

SEE ALSO: Archaeological Classification; Archaeometry; Compositional Data Analysis; Factor Analysis; Inferential Statistics; Mathematics; Predictive Modeling; Statistics and GIS; Statistics in Archaeology

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Network Science

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Network science is the study of the collection, management, analysis, interpretation, and presentation of network data (Brandes et al. 2013). Network data consist of a set of nodes (individual or collective “actors” in a network) and associated edges (sometimes called relationships, connections, or links) defined between pairs of nodes. Nodes and edges can also be assigned attributes representing additional information such as the weight or type of ties, or the size or type of node. One of the most common goals of network science is the exploration of dependencies among edges, nodes, edge attributes, node attributes, or any combination thereof. A dependency simply refers to how nodes or edges relate to each other and how they affect each other’s behavior, existence, or outcomes across a network. Dependencies can be formally expressed as theories, with associated expectations for the importance and role of specific kinds of relationships in a given network.

In archaeological applications of network science, nodes are used to represent analytical categories defined by the archaeologist: for example, people, communities, objects, places, and events. Edges represent relationships between these categories as defined by the researcher: for example, friendship, proximity, similarity, and co-presence. Archaeologists often represent their theories about relationships among the objects of study as formal theories of dependencies, and use network science techniques to explore, visualize, and analyze networks in light of these theories: for example, the relationship between interaction and power dynamics among past communities, the structural factors or node/edge attributes influencing the spread of innovations through

past social systems, or the structure and evolution of transport or economic exchange systems.

Network science and related network approaches more generally have a particularly long history in the social sciences, and have become increasingly popular in many other disciplines since 2000 (Freeman 2004). Networks have proved useful for the study of phenomena as diverse as power grids, the Internet, transport systems, neurons in the brain, food webs, scientific collaboration, and the spread of infectious diseases. Although network science and related methods have seen sporadic application in archaeology since the 1960s, the approach has only gained considerable popularity in recent years (Brughmans 2013; Collar et al. 2015). This increase in popularity can at least in part be attributed to the more widespread availability of the computational resources needed to study large networks, the availability of user-friendly software, the popularity of network science in many other disciplines, and the rise of online social networks in the early 2000s, stimulating research in networks across all disciplines.

Archaeological applications of network science are extremely diverse, covering a wide variety of relational phenomena and ways of using network data for representation (for reviews, see Brughmans 2013; Collar et al. 2015; Knappett 2011). Despite this diversity in data and methods, one can distinguish two overarching groups of common approaches that draw on somewhat different network science techniques: (1) applications focusing on the representation of archaeological datasets as networks in order to characterize and analyze structural features of those networks, and empirically test theories regarding the relationships between network structure and attributes; (2) applications focusing on formally modeling theories representing the evolution of a past network, or a dynamic process taking place over a past network, through computational modeling, simulation, or related methods. In practice, many applications combine both approaches.

The first group of archaeological applications of network science typically relies on exploratory

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techniques to aid visual exploration of datasets (such as different network layout algorithms), as well as the statistical exploration of datasets through analysis of structural properties of individual nodes or of networks as a whole (for example, centrality measures or network clustering metrics). Recent applications of such exploratory network approaches have relied on many different kinds of data for defining formal networks ranging from the physical locations of nodes, to similarities in or co-presence of material cultural categories, to line of sight visibility and geochemically sourced raw materials or objects (by no means a complete list). A particularly common approach in recent archaeological network studies has been the representation of archaeological sites or other units of analysis as nodes, while using the similarities between assemblages at pairs of sites as a means for defining edges. A wide diversity of similarity or distance indices can be used to create such archaeological similarity networks, although the most common in recent work have been co-presence of object types on pairs of sites and the Brainerd-Robinson similarity index. Common research topics addressed through such empirical networks include explorations of how network structure influences the attributes of individual nodes, or how node or edge attributes influence network structure and dynamics.

The use of exploratory network techniques is to some extent an equivalent alternative to other graphical and exploratory data analysis (see EXPLORATORY DATA ANALYSIS (EDA)) approaches more commonly used to explore archaeological data, such as tabular and geographical representations of data or summary statistics of datasets. However, network representation and exploration helps archaeologists to think explicitly about the role of relationships, which is often considered an advantage in archaeological research contexts studying relational phenomena. Moreover, many exploratory network techniques are developed to study patterns in an archaeological dataset that could not be derived without representation as a network data (such as paths through a network; the steps to take to get from node A to node B over the network; higher order relationships between sets of nodes), and therefore do not have equivalents among more frequently used tools in the archaeologist's toolbox. Network approaches are particularly well-suited to archaeological

research contexts where theories about the relationship between network structure and attributes can be explicitly formulated as expectations for patterns in formal networks. Such expectations can then be identified, analyzed, and visualized using exploratory network science techniques in order to evaluate specific theories. For example, Peeples and Haas (2013) defined networks of similarity based on the frequencies of different ceramic wares at archaeological sites across a large portion of the US Southwest, and then defined a measure of "brokerage" which was designed to characterize the degree to which each site served as an intermediate in relations spanning the network as a whole. They then used this empirical archaeological network to evaluate two competing theoretical models derived from the sociological literature on the expected relationship between brokerage and the growth and persistence of nodes, by comparing network structure to the attributes of individual nodes.

The second group of applications relies on computational modeling methods such as agent-based modeling or statistical network modeling for formally representing and testing theories of dependence. Common research topics include the spread of cultural innovations or the spread of information over past networks. For example, Graham (2006) studied the speed of the flow of information over different parts of the Roman road network, as it is known to us from historical sources. In another set of applications it is the network structure itself that is generated and evolved through a hypothesized dynamic process. Particularly common research topics include the interactions of past communities generating exchange network structures. For example, Knappett, Evans and Rivers (2008) modeled incoming and outgoing relationships of maritime interactions between Middle Bronze Age island communities in the Aegean. Where possible, the hypothesized theories of dependencies can also be validated or falsified with archaeological data. For example, Brughmans and Poblome (2016) modeled a process of trade in Roman tableware taking place over a hypothesized commercial network of Roman traders, and compared the simulated distributions of tableware with the archaeologically observed distributions to evaluate the plausibility of their theory.

Despite the increased popularity and the wide diversity of archaeological applications in recent years, network science still faces a number of daunting challenges for archaeological applications (for an overview, see Brughmans, Collar, and Coward 2016). One of the primary challenges relates to the uncertainty among archaeologists with regard to when and for what kinds of questions it is appropriate or useful to use network science techniques. Simply conceptualizing and describing a past phenomenon under study as a network (for example, a social network or a transport network) in itself is usually not a sufficient motivation to use network methods. Networks, in and of themselves, do not represent past phenomena, but rather are merely a formal way of exploring our archaeological data and theories about relationships. Another major challenge concerns the fact that many network science techniques have been imported from other social science fields and were not designed with the particulars of archaeological data in mind. Thus, a critical assessment of the specific assumptions and functions of particular techniques should become common practice before applying any “off the shelf” methods for archaeological study. A critical assessment of network techniques also implies an evaluation of the potential impacts of missing or imperfect data: sometimes archaeological data are too fragmentary to allow the use of specific network science techniques, or sometimes missing data will require a dramatically different way of interpreting the results of this technique than in the social science context where the method originated. Beyond this, the prominence of existing network science techniques commonly developed for research in the social sciences tends to stimulate the study of person–person relationships, sidelining the person–object and object–object relationships so fundamental in archaeology. This suggests that archaeologists may benefit from moving beyond the most common methods and beginning to explore a broader diversity of techniques, such as two-mode and affiliation networks, multiplex networks and interdependent networks, and longitudinal or temporal networks. Importantly, archaeologists also have the potential to help to expand the range of existing network science techniques through our focus on long-term change in social systems and spatial

data. Archaeology uniquely offers information about long-term changes in human behavior and society, whereas many temporal network science techniques are only developed for cases in the social sciences with a much finer chronological accuracy. Further, archaeology has a strong tradition of spatial analysis (see SPATIAL ANALYSIS), which many researchers have lamented has been woefully underexplored in network science more generally. Thus, although the challenges are considerable, we argue that the future for network science in archaeology is bright.

SEE ALSO: Exploratory Data Analysis (EDA); Neural Networks; Simulation Modeling

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Neural Networks

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Artificial neural networks (ANNs) are computational algorithms (see COMPUTER APPLICATIONS IN ARCHAEOLOGY) inspired by the structure and functioning of the human brain. ANNs improve the performance of a particular task, without being reprogrammed. In general, ANNs have demonstrated to be very suitable for applications in which no model exists, but a basic set of input examples is given. In medicine, for example, ANNs are used to recognize diseases from a variety of health-related indices (for example, a combination of heart rate, levels of various substances in the blood, and respiration rate). In this case, no specific algorithm exists on how to identify the disease, but a set of representative examples of all the variations of the disease are known. More examples can be found, for example, in business-related domains, sociology, psychology, and manufacturing.

ANNs are applied in different areas because of their easiness to use and implement, their capacity to approximate any mathematical function, and their ability to obtain results from complex and inaccurate data. ANNs are adequate to solve problems related, for example, to the recognition of shapes or patterns, prediction, coding, control, and optimization.

Human brain, in which ANNs are inspired, is made up of cells called neurons highly interconnected by synapses where the transmission of information occurs. Likewise, ANNs consist of a set of processing units, *nodes* or *neurons*, massively joined by connections with an assigned adjustable parameter or *weight*. The activity carried out by an artificial neuron is simple: It receives information from nearby neurons, weighted by the connections weights (the sum of these weighted signals is the neuron input), and, by applying a certain mathematical function, the *transfer function*, calculates an output. As

opposed to conventional processors (present in most computers), which transform the information sequentially, according to a program stored in the memory, the processing units work in parallel in ANN systems.

The operation of an ANN consists of providing a set of output values for each input dataset. The output provided by the network depends on the structure of the network and the values of the weights. The set of numerical values representing that scheme of weights has not been programmed, but the network is able to *learn it* through a training process during which the connections among neurons are modified and adapted, according to a certain algorithm called a *learning or training algorithm*. After the training, the particular scheme of weights and transfer functions achieved are an internal code that allows the network to react correctly to future situations or data of the same kind as those used for training, but which it has never seen before: that is, the network gains *generalization* capacity. Therefore, the knowledge of a neural network, as opposed to a conventional processor, is not stored in a memory but distributed through the network itself.

A system with these features presents a number of advantages over a conventional processor. Each unit performs a simple computation and the reliability of the total computation performed by the system depends on the interaction in parallel with a large number of units—so that the system can continue its normal functioning, even if a small part of it has been damaged. Moreover, ANNs are able to work with distorted or incomplete information due to their capacity for generalization.

In summary, as Haykin (2009) points out, ANNs are inspired by the structure of the nervous system, with the intention of creating parallel, distributed, and adaptive information processing systems. These features allow them to solve problems characterized by a high degree of complexity, inaccuracy, and uncertainty.

There are two main aspects that characterize an ANN and determine its functioning: first, its

architecture, in other words, the way neurons are organized and the way information is transmitted among them; and, second, the training mechanism. Regarding the architecture, we can consider ANNs to be feedforward or recurrent networks. In feedforward networks, neurons are distributed in layers: an input layer which receives information from the exterior and an output layer which sends the results to the exterior; there can be one or more intermediate layers or *hidden layers* between them. These networks are the simplest with regard to implementation and they also make quick calculations. On the contrary, in the case of recurrent networks, neurons can be connected to neurons from previous layers, from their own layer, or to themselves, so the concept of layer disappears. These networks imitate more accurately the structure of the brain where feedback phenomena are essential.

Attending to the learning mechanism, a distinction tends to be made between supervised and unsupervised learning. The fundamental difference between these learning mechanisms is within the existence of an external agent (supervisor) that controls the learning process. The supervisor checks the network output in response to a particular input and, in the event that the output does not coincide with the expected one (ideal), the weights of the connections are modified in order to bring the output obtained closer to the expected one. The process of adjusting weights is performed iteratively and can be carried out in different ways. This type of learning is very useful in classification and function approximation problems. On the contrary, in an unsupervised learning mechanism, the network does not receive any information to indicate whether or not the generated output is correct. There are no comparisons to predetermined ideal responses. The network function is to find the regularities or categories that can be established among the data presented at the input. Data requirements for unsupervised learning are thus much easier and less costly to meet, but the capability of the network is significantly less than in the case of supervised learning.

In order to understand the increasing use of ANNs in the field of archaeology, it should be taken into account, as pointed out by Deravignone, Blankholm, and Pizziolo (2015), that one of the main characteristics of this discipline

is the fact of dealing not only with very complex phenomena, such as culture, society, and past economic aspects, but also with limited and imprecise datasets. In addition, the generalization capacity of ANNs allows for carrying out the data analysis without preconceptions or subjective influences, such as the a priori application of a theory or model. Moreover, it is worth mentioning the ease of ANN integration into automated systems, both for acquiring data and for carrying out the data discrimination or classification process. A review of the literature on the application of ANNs to archaeological data shows that most used models of supervised learning network relate to the multilayer perceptron (MLP), and those models of unsupervised learning network relate to self-organizing maps (SOM).

The MLP is one of the most used ANNs in any field; to the point that many people identify ANNs with this architecture. MLP is a feedforward network, using the *backpropagation error algorithm* as its learning algorithm. In MLP networks, a set of values whose output is known, the *training set*, is used, so that the weights are modified in order to minimize the error, that is, the difference between the desired response and the system output. The error information is entered back into the system by adjusting the system weights. A backpropagation network, containing at least one hidden layer with enough nonlinear units, can learn any type of function or continuous relationship between a group of input and output variables. This property turns the MLP into a flexible and nonlinear general-purpose tool. Attention must be paid to overtraining, which occurs when the network begins to “memorize” training data instead of “learning” to generalize from trend.

SOM are an example of unsupervised learning networks used in archaeology. This type of network is composed of two layers: the input layer and the output layer; the latter is organized as a two-dimensional map. The connections are feedforward and the learning is competitive; this means that only one of the output neurons (or a group of neighbors) is activated when an input pattern is presented to the network. The objective of this training is to categorize (cluster) the input data. SOM are normally used to provide visual aids because they allow to show the relationships among large

amounts of data that would require more dimensions (something impossible for humans) to be displayed properly.

Regarding applications of ANNs in archaeology, they can be included in the following types: the identification of geographic areas with high archaeological potential and the classification and/or discrimination of archaeological materials or sites. In this sense, Anemone, Emerson, and Conroy (2011) used an MLP to predict productive fossil localities by means of remotely sensing imagery data; the network was trained to recognize the spectral characteristics of known productive localities and other land cover classes in the area of study. The results of the classification were examined within a geographic information system (GIS) software package in order to determine which areas had a high potential of being fossiliferous, due to the similarity of their spectral signatures to those of known fossil localities. A similar method was applied by Deravignone et al. (2015) in order to predict the location of medieval Tuscan castles. The variables they used as the input of the network came from raster layers of the GIS, such as elevation, slope, distance to watersheds, and others related to social or economic aspects, such as the distance from other settlements or from the raw materials. The output is a predictive raster map for this kind of settlement. Regarding the classification of archaeological materials, the eventual objective of a number of studies was the automation of the process. In this sense, Ramil, López, and Yáñez (2008) and Aprile, Castellano, and Eramo (2014) applied MLP to archaeological potsherds. In the former case, the classification was based on laser-induced breakdown spectroscopy (LIBS) (see LASER-INDUCED BREAKDOWN SPECTROSCOPY (LIBS)) data and the network was trained to recognize the characteristic LIBS spectra of sherds from different provenances. In the work of Aprile et al. (2014), digital images were used for petrographical (see PETROGRAPHY AND CERAMICS) classification. In a different line of investigation, Nash and Prewitt (2016) used the MLP to identify patterns in projectile point typology. Moreover, Coppa et al. (2007) applied SOM to dental metrics (see DENTAL METRICS) data in order to determine that seven human teeth belonged to the same individual. In paleoanthropology, it is common to deal with missing

data, due to the difficulty of finding complete skulls, skeletons, or dentitions, which makes the analysis by other statistical methods, such as principal component analysis (PCA), difficult or even impossible. The application of ANNs avoids this problem and, furthermore, SOM is an unsupervised technique which is able to display overall similarities of the processed data and facilitates easy visualization and interpretation.

In summary, neural networks provide archaeologists with new tools from the field of artificial intelligence (see ARTIFICIAL INTELLIGENCE) to analyze the past. The algorithms mentioned in this entry and others that have been successfully used in various fields of science and technology can probably be applied to many other archaeological problems, such as pattern recognition in rock art, use-wear analysis of lithic tools, paleoecology studies, analysis of land utilization, or even migration and colonization scenarios for past human populations. Therefore, scientists and archaeologists should work together and their efforts will be rewarded with a deeper knowledge of our past.

SEE ALSO: Archaeological Classification; Archaeometry; Network Science; Parallel and Distributed Computing; Predictive Modeling; Statistics in Archaeology; Supervised Pattern Recognition

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Nonparametric Statistics

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Nonparametric statistical methods provide an approach to analyzing data wherein the parameters of the underlying population from which a sample is taken are unknown. These methods therefore make mild assumptions about the data, rather than the more stringent assumptions required by parametric methods (see REGRESSION AND CORRELATION ANALYSIS; SAMPLING THEORY; ANALYSIS OF VARIANCE AND COVARIANCE; and DESCRIPTIVE STATISTICS). Primary among the assumptions in the parametric analytical approach is that data are normally (Gaussian) distributed in the population sampled. As nonparametric methods do not rely on this assumption, among others (such as linearity), they make useful alternatives to parametric methods when the statistical assumptions of the latter are violated.

The basic principles of nonparametric approaches and their application are reviewed herein. There are dozens of nonparametric methods available, some of which correspond to analogous parametric methods, such as two-sample mean comparisons (e.g., Student's *t*-tests), linear regression, correlation, and the analysis of variance. Given the breadth of nonparametric methods available, only a summary of these methods and their application is discussed herein. Emphasis is placed on the application of methods to address archaeological areas of inquiry.

All statistical methods are concerned with estimating measures of central tendency and the dispersion of data around those measures. Unlike parametric methods, which estimate the mean and the variance, nonparametric methods often use the median and the quantity of data on either side of the median. Thus, nonparametric methods are, overall, distinguished by ignoring magnitudes of data and instead focusing on the ranks of those data relative to each other. Because of this

approach, nonparametric statistical approaches are more resilient to the effects of outliers, skewed distributions, and kurtosis of data (Gibbons 1992). In addition, these methods allow the analysis of data that are not interval scale, such as ordinal and nominative data. Percentage data and ratios also should only be examined using nonparametric methods, the reasons for which are outlined in Allison et al. (1995).

An important limitation to all nonparametric methods is that they generally have less statistical power compared with parametric counterparts, given the same sample size and effect size (Zar 2009). Statistical power measures the ability of a statistical test to detect a significant result when one is actually present; tests with less power are more likely to fail to detect a result when it is present. Only when the requirements for parametric techniques are violated are nonparametric tests more statistically powerful (Buskirk, Willoughby, and Tomazic 2013).

Good statistical practice suggests that researchers determine the most appropriate methods for analysis *before* data collection commences (Zar 2009). Choosing between parametric and nonparametric methods, however, may not be possible until descriptive statistics and tests for normality are conducted on data. A key point to understand is that nonparametric statistics may always be used for assessing most questions, though in cases where statistical assumptions are met, parametric methods provide more robust results. In addition, many nonparametric techniques are versatile, and so the brief examples that are introduced here are not meant to be indicative or exhaustive. Researchers should consult the literature to see how these methods have been applied, or to ascertain whether there is a precedent for applying certain methods to the data in question.

Perhaps one of the most commonly encountered families of nonparametric methods are chi-squared analyses (see CHI-SQUARE ANALYSIS), which often are used as goodness-of-fit tests. Chi-square tests of association examine whether nominal frequency data are independently assorted among categories between two

nominal variables. That is, using this method, the presence of one trait, character, or state is not contingent on the presence of another; hence, this is the reason why the table used for these analyses is termed the contingency table (see Table 1 for an example). Archaeologists may use these analyses to evaluate whether the distribution of artifacts or other objects, for instance, is the same among features within a site, among temporal horizons, or between sites. In the example presented in Table 1, lithic points recovered from a site are categorized by two nominal variables: source material location and point type. The totals for rows and columns are used to calculate the expected frequencies for each value, which in turn are used to determine whether the lithic points in these two categories are independent; that is, are the lithic types associated with the raw source material?

Chi-squared analyses experience the benefit of simplicity in their calculation, but have limitations. Chief among this is if expected values are less than five, then chi-squared analyses may yield false results (i.e., type I (false positive) or type II (false negative) errors). One solution is to combine nominal variable categories, though this is generally not ideal, especially when levels of nominal variables are specifically chosen to address research questions. Alternatively, researchers may use nonparametric Fisher's exact tests or random resampling tests (such as those based on Monte Carlo) to address this limitation (Buskirk et al. 2013). In addition, chi-squared contingency tables cannot assess whether an observed frequency is different from one that is expected (for instance, if an isotopic frequency

is greater than expected); to perform this type of analysis, a binomial test should be used.

When examining the association of two variables measured on an ordinal or interval scale, we commonly think of correlation. Pearson's correlations, however, make parametric statistical assumptions, and so are inappropriate when data are not normally distributed or errors are correlated (as these will inflate correlations) (but see Chok 2010 for an alternative perspective on the resilience of Pearson's correlation in non-normal data). Two alternative correlation techniques are Spearman's rho and Kendall's tau. These correlation methods use a version of data ranking to determine the amount of independence between two variables. Kendall's tau has been shown to be more robust than Spearman's rho, in part because Spearman's rho is limited to bivariate correlation, while Kendall's tau may be computationally modified to calculate partial correlation coefficients (Siegel and Castellan 1988). Partial correlations examine the independent relationship of two variables while accounting for the shared correlation with one or more other variables. For example, one may want to assess the association between the weight of tempering materials used in ceramics and the size of vessels while accounting for the effect of paste weight.

Commonly, researchers want to know if measures of central tendency (i.e., means or medians) indicate that variables were taken from different source populations. In parametric statistics, these inquiries use a class of methods that fall within the general linear model, which includes Student's *t*-tests and the analysis of variance (ANOVA). There are multiple nonparametric analogs to these approaches. A variable in two

Table 1 Example of a contingency table used for chi-squared analysis of lithic points recovered from a single site and temporal horizon. The contingency table with frequencies of points and totals within each nominal category is shown on the left. Expected values, calculated using the chi-squared formula (Zar 2009), are presented on the right.

		<i>Lithic point type</i>			<i>Expected values</i>	
		<i>Fluted</i>	<i>Nonfluted</i>	<i>Total</i>	<i>Expected Shared</i>	<i>Expected Not shared</i>
<i>Source</i>	Local	23	12	35	21.94	13.06
	Exotic	19	13	32	20.06	11.94
	Total	42	25	67		

independent samples may be compared using the Wilcoxon–Mann–Whitney test, which is a blending of two ranking methods (the Wilcoxon rank-sum test and Mann–Whitney U test). This test is especially useful to determine whether one group of observations is shifted with respect to the other group, such as if the concentration of cultivar remains is the same between two sites, or between two time periods. Paired samples, such as those taken before and after an experimental treatment, are best compared with a modification of the Wilcoxon test, the signed-rank test. Alternatives are available for this test if data are paired and dichotomous: the sign test and McNemar’s test. These are less frequently encountered in archaeological settings, but they are useful when threshold effects or a single change in state is under observation. Finally, in the case where researchers wish to compare a variable among more than two groups, a nonparametric extension of the one-factor ANOVA is available through the Kruskal–Wallis test, which is an extension of the ranking methods used in the Wilcoxon–Mann–Whitney test and approximates a chi-square sampling distribution. Similarly, Friedman’s test, an analog of the repeated measures of ANOVA, allows comparisons of more than two related measurements, and so is an extension of the Wilcoxon signed-rank test. Kruskal–Wallis and Friedman’s tests are superior to multiple Wilcoxon–Mann–Whitney tests, as the former testing methods reduce the probability of a type I error that occurs when making multiple comparisons, much as an ANOVA reduces this error for Student’s t -tests (Zar 2009). The Kruskal–Wallis test results indicate whether the median of a variable differs between groups, but cannot show which group or groups differ. Likewise, Friedman’s tests only indicate if a change in a measure for a variable occurs between bouts for paired data. A post-hoc comparison test—which is like using multiple pairwise comparisons while mitigating the probability of type I error—can indicate which groups differ. The Nemenyi test is one such post-hoc method (see Zar 2009 for a more complete discussion of this test).

All the group comparison tests noted in the above paragraph may also be accomplished using resampling and permutation methods. With the emergence of fast computing power and software (see below), bootstrapping has

emerged as a common form of resampling. In a bootstrap with replacement, data are sampled a set number of times, and parameters (means, medians, variances) are calculated for each iteration. For example, in a dataset of 20 observations for a variable, a bootstrap with 100 iterations will sample 20 observations from the original data *with replacement*, and the mean of the sampled means for the 100 iterations may be compared against a comparative observed or expected mean. Similarly, the bootstrap may be used to calculate confidence intervals around an estimated parameter, which may be used in lieu of a p -value to show if groups significantly differ. This method circumvents the necessity of assuming a distribution for the data. Another approach is to determine parameters for each possible sample that may be taken from observed data *without* replacement. This methodology is the basis for permutation tests, which generally operate by comparing the test statistic (e.g., for a Wilcoxon–Mann–Whitney test) for the original observed data against all the random reorderings of those data, which, in the case of independent sample comparisons, are made between groups. A variety of applications of these permutation tests are available (Good 2005), and may be applied from one-sample tests to ANOVA and regression.

Often, researchers want to know the effect of one variable on another, and not their association or differences; this is measured through regression analysis. Regression analysis examines the relationship between two or more variables by plotting the values of one (or more) predictor variables against a predicted (or criterion) variable. In parametric methods, regressions have a series of assumptions that require large samples, normality, and homoscedasticity of data, as well as relationships between data that are linear, quadratic, or cubic. Often, such as with growth data, cyclical data, or variable data (e.g., atmospheric concentrations of carbon isotopes), such relationships cannot be assumed. For this reason, the relationship between variables described in a regression may best be represented by a weighted fit line, the LOESS (locally weighted scatterplot smoothing) regression (Fox 2000). This method uses a kernel function, wherein the density of data around each point in a data range is assessed, and points with greater data densities are given

greater weights. These weights are used to iteratively generate a smoothing polynomial line that presents the trend between the predictor(s) and the criterion.

A key conclusion to draw from the approaches listed above is that multiple methods are available to assess questions raised within archaeological fieldwork and laboratory work. Additional nonparametric methods, including those that use maximum likelihood and Bayesian approaches (see BAYESIAN STATISTICS), are available for comparing variables, groups, and parameters. Given the ongoing development of these methods, it is important to read broadly in the science literature and observe how other disciplines are applying nonparametric statistical tests. With ever-faster and greater availability of computers, these methods are becoming more common. Commercially available packages, such as SAS, SPSS, Stata, NCSS, and JMP, are all regularly updated to include more nonparametric methods and options. Perhaps the best software resource, however, is R (R Core Team 2013), which is freely available and has user-created software packages that include many statistical tests not yet available in other software, such as the Nemenyi test. Regardless of the software employed, careful consideration of the theory and applications of any statistical method must be undertaken to optimally and accurately arrive at answers to archaeological questions.

SEE ALSO: Philosophy of Science

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FURTHER READINGS

Poisson and Binomial Distribution

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The binomial and Poisson distributions are two statistical methods suitable for calculating discrete archaeological phenomena, which means that they have been used for assessing the probability of the outcomes that occur. This section introduces these two distributions and comparatively shows their differences and similarities.

The binomial distribution is a means to model the likelihood of discrete multiple phenomena in which only two possible outcomes are possible, such as the presence or the absence of material evidence in a given archaeological context (Banning 2000, 124–125). The two possible outcomes of this distribution are generally designated as “success” (p) or “failure” (q). The binomial distribution describes the behavior of a random count variable X only if all the following conditions are met: (1) the number of trials (n) is fixed; (2) each trial has two possible outcomes as “success” (p) or “failure” (q); (3) the probability of success p is the same for each trial; (4) each trial is independent, meaning that the outcome of one trial does not affect that of any other. The binomial distribution is applied to cases such as coin flipping, where there is a fixed number of trials, the outcome is either a head or a tail, the probability of success (e.g., getting a head) is $p = 0.5$ for each trial, and the outcome of one flip does not affect the outcome of other flips. For the case in which a coin is flipped ten times and the number of heads is counted, the parameters of the binomial distribution will be the number of trials $n = 10$ and the probability of success $p = 0.5$, and the distribution is conventionally abbreviated as $B(10, 0.5)$. This means that there is a 50 percent probability of getting a head when flipping a coin ten times. Given that there are only two

possible outcomes, the probability of success (p) in flipping a coin for each trial is $P(p) = 0.5$, and the probability of failure (q) is $P(q) = (1 - p)$, which is $1 - 0.5 = 0.5$. Instead, the number of sixes by rolling a die ten times has a binomial distribution $B(10, 1/6)$. So, the probability of success p for each trial is 0.167, while the probability of failure q is $1 - 0.167 = 0.83$. In archaeology there are several different applications for the binomial distribution. For instance, paleobotanists use binomial distribution to measure the presence or absence of particular plant taxa in a fixed number of samples (Popper 1988, 63). This distribution has also been used to assess at the site of Casas Grande the likelihood of a co-occurrence of a particular decorative motif with male or female effigies (VanPool and VanPool 2006).

For instance, the binomial distribution can be applied to a scenario where the probability of finding an arrowhead in an excavation unit of 1 m^2 is 0.3, and the excavated units are 10. In this case the binomial distribution is symbolized as $B(10, 0.3)$. Therefore, it is possible to calculate the probability of finding one or more arrowheads in a given number of trials. Probabilities of a random variable X can be found by applying the following formula (VanPool and Leonard 2011, 80–81):

$$P(x) = \frac{n!}{x!(n-x)!} p^x (1-p)^{n-x} \quad (1)$$

where $P(x)$ is the probability of success out of n trials, x is the specified number of successes (finding an arrowhead), n is the fixed number of trials, p is the probability of success on any given trial, and $(1 - p)$ is the probability of failure (q). The expression $\frac{n!}{x!(n-x)!}$ is known as binomial coefficient and the notation $n!$ stands for the factorial of a number, which can be calculated by multiplying a given number by all integers between itself and 1 (e.g., $3! = 3 \times 2 \times 1$).

Using Equation (1) it is possible to get the probability of finding four arrowheads (x) after

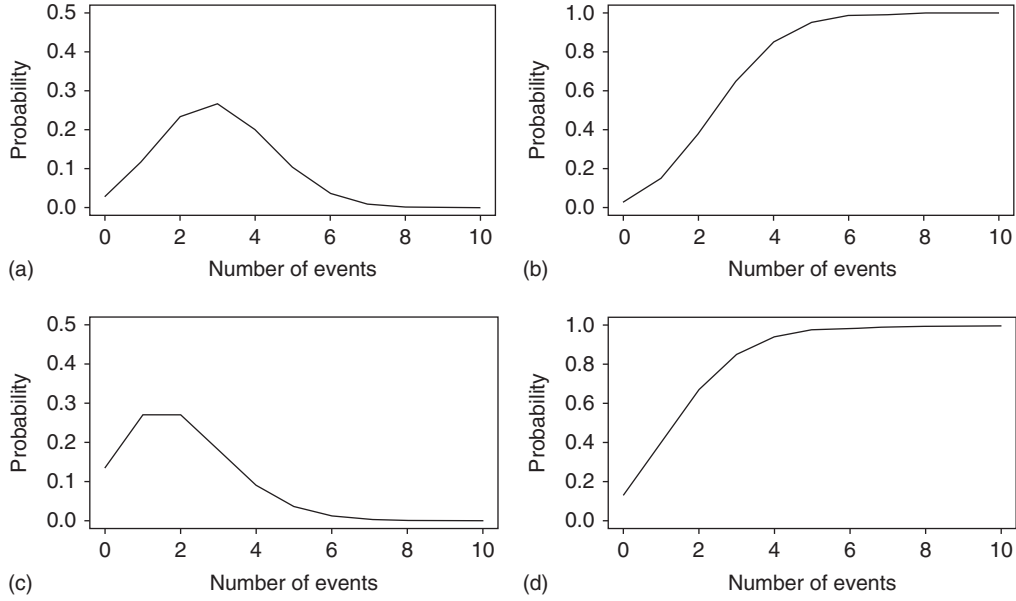


Figure 1 Probability (a) and cumulative distribution function (b) for binomial distribution B(10, 0.3), and Poisson distribution with $\lambda = 2$ (c, d).

excavating ten excavation units:

$$\begin{aligned}
 P(4) &= \frac{10 \times 9 \times 8 \times 7 \times 6 \times 5 \times 4 \times 3 \times 2 \times 1}{4 \times 3 \times 2 \times 1 (10 - 4)!} \\
 &\quad \times 0.3^4 (1 - 0.3)^{10-4} \\
 &= 210 \times 0.3^4 \times 0.7^6 = 0.20
 \end{aligned}$$

Figure 1 (a) and (b) shows the different probabilities and density function of finding zero to ten arrowheads and the cumulative distribution for the binomial distribution (10, 0.3).

The probability of finding from zero to four arrowheads is then the sum of these probabilities. The probabilities are 0.03, 0.12, 0.23, 0.26, and 0.20. Hence, the probability of finding four or fewer arrowheads is 0.84. The cumulative probability of finding more than four arrowheads after excavating ten excavation units is $1 - 0.84 = 0.16$.

Continuing excavating over and over again it is possible to calculate the long-term average of the expected successes (number of arrowheads found) over the entire population of trials (excavation units). The mean of a binomial random variable X is calculated by the following formula:

$$\mu_x = np \quad (2)$$

where n is the number of trials and p the probability of success. Hence, the mean of the binomial distribution after digging 20 excavation units is $np = 20 \times 0.3 = 6$.

The variance of the random variable X is $\sigma^2 = np(1 - p)$ and the standard deviation of X is just the square root of the variance, which is $\sigma = \sqrt{np(1 - p)}$. The variance in the binomial distribution B(20, 0.3) is $6(1 - 0.3) = 6 \times 0.7 = 4.2$, and the standard deviation is the square root, which is 2.05.

The Poisson distribution is useful for modeling and finding the probability for the number of events occurring in a specific interval of time or within a given area of space. A random variable X , the number of events in a fixed unit of time or space, has a Poisson distribution when the following assumptions are true: (1) the events occur independently of each other; (2) the average frequency that an event occurs in a fixed time or space does not change through time; (3) two events cannot happen simultaneously; (4) the probability of the occurrence of an event in a fixed interval is proportional to the length of the interval. Unlike the binomial distribution, the Poisson distribution does not model the

probability of the frequency of “successes” (p) or “failures” (q) occurring in a fixed number (n) of trials. Instead, it provides the expected number of events in a fixed unit of time or space. This distribution is usually used to test if specific events were generated by a random process. In addition, because the Poisson distribution is characterized by no fixed cutoff, the random variable X can be a positive integer from zero to infinity. The Poisson distribution closely approximates the binomial distribution when n is large, p is very small (one rule of thumb is that it should be no greater than 0.1), and $\lambda = \mu_X$. The Poisson probability of any given number of the variable X can be calculated with the following formula:

$$P(x) = \frac{\lambda^x e^{-\lambda}}{x!} \quad (3)$$

where x is the number of the events whose probability is calculated, λ is the average number of events occurring per unit of time or space, e is a constant that is approximately equal to 2.71828, and $x!$ is the factorial number of x .

The Poisson distribution can be useful to model events such as the number of patients arriving at an emergency room between 10 and 12 am, number of goals scored in a World Cup football match, the number of students enrolling at a university in a year, the number of phone calls received by the Police’s phone center between 11 and 12 pm, and so on. In archaeology the Poisson distribution has been generally used to test if past events have randomly occurred per unit of time and space. For instance, the rate of disintegration of radioactive ^{14}C per minute is described by a Poisson distribution (Banning 2000, 125; Buck, Cavanagh, and Litton 1996, 105). This distribution has also been used to assess if the spatial configuration of archaeological artifacts or sites in a given study area is the result of past random processes (Bevan et al. 2013; Crema, Bevan, and Lake 2010; Palmisano 2013).

Using Equation (3) it is possible to calculate the probability of the number of events (e.g., artifacts or sites) found within a given spatial unit (e.g., a square). For instance, in a scenario where 20 events are found in ten squares, and λ is 20/10 = 2, the probability of an empty square is given by the following formula:

$$P(0) = \frac{2^0 (2.718\ldots)^{-2}}{0!} = (2.718\ldots)^{-2} = 0.135$$

and the probability of a square containing one event is

$$P(1) = \frac{2^1 (2.718\ldots)^{-2}}{1!} = 2 \times 0.135 = 0.27$$

Probabilities for larger values of X are calculated in the same way to obtain the distribution shown in Figure 1c.

Although the graph does not show the probabilities for values higher than ten, this is just to save space. In fact, there is a low probability of having a square containing ten or more events. In the Poisson distribution it is theoretically possible to have hundreds of events within one square, even though that probability would be extremely low. Figure 1d shows the cumulative probability from zero to X for any specific value of X . This is useful to obtain the probability of finding more or fewer X events within a square. In the present example the probability of finding one or no events in a square is $0.135 + 0.27 = 0.405$. Once all probabilities are found, then it is possible to calculate the expected number of squares that can contain X events by multiplying the relevant probability by the total number of squares (Lloyd 2011, 248–249). In this case, the expected number of squares containing zero and one event is 1.35 and 2.7 respectively. Instead, the expected number of squares containing four events will be $0.09 \times 10 = 0.9$.

Comparing the expected frequencies with the observed data allows one to assess if the events are distributed randomly in a given study area. For instance, the expected number of squares containing ten events (0.0003) is close to zero according to the Poisson distribution. Nevertheless, if in the observed data there are one or more squares containing ten events, it means that the number of squares containing X events is more than expected and the events are clustered in one or more parts of the surveyed area. Poisson models are, therefore, useful to assess how well a null hypothesis of complete spatial randomness explains the observed distribution of artifacts or sites in a given study area.

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Pottery Data Quantification

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What is pottery data?

Pottery sherd used to be one of the most overlooked artifacts found on excavation sites, because of its relative ordinariness and its frequent occurrence. Even though pottery sherd is still not considered to be esthetically appealing, the view on its importance changed slowly throughout the twentieth century, mostly because of the development of archaeology and the straightforward evolution of our ability to extract data. This development was accelerated even further by the application of interdisciplinary approaches, especially by computer technologies during recent decades. Pottery is now considered to have great potential for revealing additional information about its user and society, from analysis of the fabric, shape, and additional features of the pottery. Experienced specialists are able to extract information about the social and economic status of the user, his or her cultural affiliation, cultural development of the society, culinary habits, trade networks in the area, and so on. We can determine its *class* (e.g., plate, crater, cup), *form* (e.g., volute crater, column crater), *vessel size*, and *vessel thickness* from its shape. Additional features of the clay can be determined (e.g., *porosity*, *quality*), the *firing process*, and *inclusions* (granularity, grain size) from analysis of its fabric. Specialists can analyze additional features incurred by human interaction with the pottery: degree of abrasion from daily use, decoration, nondecorative deliberate markings like graffiti, potter's stamps or merchant marks, and repairs. Assessment and analysis of these straightforward attributes leads to the

extrapolation of further pottery data such as provenance, dating of the vessel, or the method by which the pottery was made (Barclay and Knight 2016).

Quantification

All the above-mentioned pottery data can be extracted from a single piece of well-preserved sherd. However, pottery is the most frequent artifact found at excavation sites and the majority of the excavated sherds are difficult to determine because they might lack features that would distinguish them from the rest of the assemblage. In order to extract data from the sherds collected from a surveyed area, specialists have developed various methods for its quantification. Orton and Hughes (2013, 21) stated that quantification is simply the answer to the question “How much pottery is there?”—whether in a context, feature, site, or other grouping. In broad terms, quantification is the measuring of the amount of each type of pottery in an assemblage, aiming to describe the assemblage in terms of the proportions of each type present and determine relative amounts of the different types of vessels present in a single context.

Common methods of quantification are as follows:

- Sherd count: counting every sherd, except those that are freshly broken. The amount is not an estimate.
- Sherd weight: recording the total weight of identified sherds.
- Estimated vessels represented (EVREP): the estimated number of vessels that are present in the assemblage.
- Estimated vessel equivalent (EVE): the most suitable measure for pottery, where a measurable fragment (usually a rim or bottom) is scored as a fraction of a complete vessel.

Using two or more of these measurements is preferable than just one; however, it is crucial to use a consistent approach for the site assemblage.

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First attempts at using multiple measurements were made in the context of count and weight by Solheim (1960) and further developed by Orton (1985), and Schiffer (1987, 282).

Estimated vessels represented (EVREP) and mosaicking

The term estimated vessels represented (EVREP) was introduced by Orton and Hughes (2013, 172) and it represents the estimated number of vessels that are present in the assemblage. Specialists who use this method have to face an issue caused by the amount of sherds which are difficult to assign to a specific vessel. While the majority of sherds come from the body of the vessel and not from the easily distinguishable parts, like rims and bottoms, the estimate might become distorted. This issue was recognized in the past and various approaches were suggested:

- Minimum vessel count: Sherds are assumed to belong to the same vessel, unless we can prove that they belong to a different one.
- Maximum vessel count: Every sherd counts as one vessel, unless it either fits into another sherd or is demonstrably part of the same.
- Average of the minimum and maximum vessel count.

However, even these elaborate estimates are not generally considered to be reliable. In order to make this estimate more precise, a different approach using computer visualization (e.g., mosaicking) is needed to minimize incorrect assignment of multiple sherds to one vessel or differentiate the sherds more successfully.

Mosaicking is the process of the reassembly of an object from its pieces and it is very similar to the automatic assembly of jigsaw puzzles. Utilizing rotational symmetry of vessels manufactured on a potter's wheel enables the possibility to assign multiple sherds to one vessel even if there are gaps between them. Figure 1a shows a box filled with archaeological fragments, which could possibly fit to each other. Figure 1b illustrates manually identified, matching fragments.

Mosaicking can be seen as a special case of object recognition by approximate outline matching. The most common technique of mosaicking is 2D outline matching. Hori, Misakazu, and Ogasawara (1999) propose a method for joint detection among two potsherds designed for pottery fragment outlines. Their approach is based on a partial verification method of a pair of contours without knowledge of the shape features of a piece. Kong and Kimia (2001) approach the jigsaw problem in two stages: The first stage, local shape matching, aims to find likely candidate pairs for adjacent fragments; the second stage



Figure 1 Box filled with archaeological fragments and matching pieces.

represents ambiguities resulting from local shape matching. Matching is based on the notion of an alignment curve to represent correspondence between two curves.

Other techniques used are 3D outline matching and surface matching of fractured surfaces. The specific problem of identifying adjacent ceramic fragments by matching the shapes of their outlines was considered by Ücoluk and Toroslu (1999). They represent the 3D fragments by their boundary curves, from which curvature and torsion scalars are computed. A noise-tolerant matching algorithm serves to find the best match of two such circular strings. There is, however, no fully functioning technique that would succeed in actually reconstructing more than a few fragmented objects from the initial acquisition, thus proposing challenges for further research.

Estimated vessel equivalent (EVE)

The basis of EVE is the assumption that every sherd represents a portion of the whole pot of which it once formed a part. Specialists might assign these proportions to sherds as “scores” and add them up to find the total amount of vessel types. In practice, it is not usually possible to assign a score to every sherd, and one is limited to sherds such as rim sherds, whose size can be measured in terms of the proportion of the whole vessel. Since we are sampling the measurable sherds from an assemblage, we refer to the EVE (Orton and Hughes 2013, 174).

Concerning the rim or base equivalents, specialists use a diameter chart to estimate what proportion of the circumference of a vessel each rim or base represents, giving a completeness index (rim-equivalent or base-equivalent) that ranges from 0 to 100 percent. Additionally, a simple mathematical method, discovered by Orton and Tyers (1990), can turn this EVE into a number that has the same statistical properties as counts of objects. This number is called the *pottery information equivalent* (PIE), because 1 PIE contains as much information as one whole vessel. If we use these PIE values to calculate proportions of pottery types, they provide unbiased estimates of the relative abundance

of each type in the assemblage (Banning 2006, 106).

However, specialists who use quantification for a better understanding of the assemblage have to face the impossibility of determining whether the assemblage is complete, or whether it contains pottery sherds contextually belonging to a single period, or, if needed, one specific group of users.

From quantification to visualization

The growing need for maximizing the potential of the quantification and minimizing the errors caused by the incompleteness or redundancy of some sherds in the assemblage leads to the utilization of a new approach. Visualization is considered to be a tool for specialists who have to process the entire excavated assemblage, which allows a new way of understanding the large amount of data and also correct identification of redundant examples.

Visualization generally uses three inputs of data:

- 3D images represent 3D objects, which allow us to consider 3D volume as part of the entire 3D world. A 3D representation is a transition of an object in the real 3D world to an object-centered coordinate system, allowing object descriptions to be independent of the viewer. In order to quantitatively describe real-world structures, methods for extracting 3D information have to be investigated.
- A digital image defined as a 2D image represented by a discrete 2D array of intensities. This represents an object's appearance in grayscale or colors, has a certain resolution, and might be stored in JPG or GIF format.
- A sequence of images (video) represents how images change due to the motion of objects, point of view, or light source. In addition to the spatial features represented in a 2D image or single frame, videos enable a representation of object motion over time.

Traditional archaeological classification and reconstruction is based on the rim profile of the object, which is the cross-section of the fragment in the direction of the rotational axis of symmetry.

This 2D plot holds important information needed in order to perform archaeological research. Both correct profile and correct axis of rotation are therefore essential to reconstruct and classify archaeological ceramics.

Segmentation of the profile section

Specialists usually acquire the profile by using various traditional methods of documentation. The most common method is to use a combination of calipers or dividers and profile/contour gauges. The outer surface of the sherd is pressed into the profile gauge, which creates an imprint on the gauge. This imprint is redrawn on paper or a graphic tablet as the outer line. Then the thickness of the sherd is measured with calipers or dividers at regular intervals or at any particularly identifiable points (e.g., change of angle). The thickness, which determines the distance between the outer and inner profile, is tracked along the outer profile accordingly. The points are then connected, creating the inner profile and thus the whole profile of the pottery.

The profile should be first segmented into its parts, the so-called primitives, in an automatic way. The determined profile has to be converted into a parameterized curve and the curvature has to be computed (Bennett and MacDonald 1975). Local changes in curvature are the basis for rules required for segmenting the profile. Emphasis is placed on a hierarchical segmentation of the profile into rim, wall, and base by creating segmentation rules based on the expert knowledge of the archaeologists and curvature of the profile. Segments of the curve are divided by so-called segmentation points. If there is a corner point—that is, a point where the curvature changes significantly—the segmentation point is obvious. If there is no corner point, the segmentation point has to be determined mathematically.

By means of these curve points, several main segments of a vessel are distinguished: the rim, upper part, lower part, neck, shoulder, belly, and bottom. On the basis of the number and characteristics of these segments, different kinds of vessels can be classified. Segmentation is carried out only on the outer half of the profile (Orton

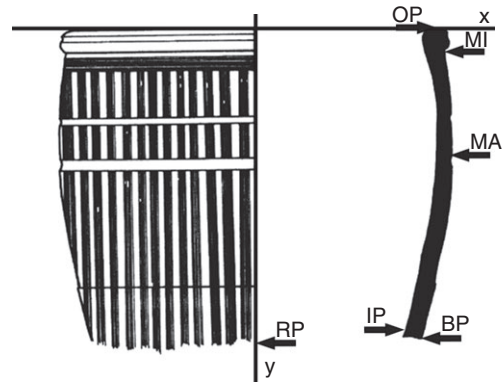


Figure 2 List of characteristic points.

and Hughes 2013), because the inner side does not contain information. The next step is to split the outer profile into its primitives by locating the characteristic points (see Figure 2):

- Inflexion point (IP): where the curvature changes its sign.
- Local maximum (MA): maximal point of vertical tangency.
- Local minimum (MI): minimal point of vertical tangency.
- Orifice point (OP): outermost point, where the profile line touches the orifice plane.
- Base point (BP): outermost point, where the profile line touches the base plane.
- Point of the axis of rotation (RP): where the profile line touches the axis of rotation.

These points are found within the transformed data. A formalized approach uses mathematical curves (e.g., cubic splines) to describe the shapes of vessels and their parts. The profile is thus converted into one or more mathematical curves (interpolation or approximation by B-splines). Figure 2 shows an example of an automatically segmented pot with the characteristic points detected.

3D object reconstruction

In order to describe the relationship between 2D image structures and their corresponding real-world structures, methods for extracting 3D information need to be investigated. According

to Marr (1982), we see 3D vision as a 3D object reconstruction task to describe 3D shape in a coordinate system independent of the viewer. The shape of a 3D object is represented by a 3D model. Two main classes of 3D models are identified: Volumetric models represent the “inside” of a 3D object explicitly, while surface models use only object surfaces. Unlike 3D models, depth maps or range images describe relative distances from the viewer of surfaces detected in the scene. For 3D object reconstruction the following three major steps are identified: (1) data acquisition, (2) range image processing, and (3) model reconstruction.

Data acquisition is the first and one of the most important tasks in a chain of 3D reconstruction tasks, because the data quality of the sensed images influences the quality of the final results. El-Hakim, Beraldin, and Picard ((2002) specify the quality of data by a number of requirements: high geometric accuracy, capturing all details, photo-realism, full automation, low cost, portability, flexibility in applications, and efficiency in model size.

Blais (2004) reviews the last 20 years of range sensor development. Each view acquired by the range sensor represents a portion of the object. Multiple views of the same object have to be combined to produce a complete model of the object. The process of combining range data into one single coordinate system is called range image registration. Approximate transformation between the views can be carried out either automatically by a calibrated robot or shifting unit or by the computation of the rigid transformations that add and track the data from one view into the other view. The most commonly used algorithm for registering is the iterative closest point (ICP) algorithm. ICP improves the registration of two overlapping surfaces by calculating the unique transformation that minimizes the mean square distances of the correspondences between the two surfaces.

The final-step model reconstruction refers to a surface fusion process, which consists of multiple tasks such as large dataset reduction, outliers removal, surface triangulation, and hole filling. The goals are to minimize global registration error, caused by the propagation of noise from

one surface patch to the other, and to preserve the topology of the original object.

The increase in large quantities of 3D data causes many complex issues for existing algorithms within the area of data representation; hence the need for revision of existing methods. Because of the rising tendency for obtaining large quantities of 3D data, the majority of existing algorithms face issues of computational complexity and data representation and need to be revisited. Important topics in 3D vision deal with scene capture and self-calibration, 3D modeling under time-varying motion, deformation, or illumination, 3D modeling from large and complex datasets, and 3D view registration and recognition.

SEE ALSO: Digital Heritage; Elemental Analysis of Pottery; Image-Based 3D Modeling

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Predictive Modeling

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Archaeological predictive modeling can be defined as a technique trying to predict “the location of archaeological sites or materials in a region, based either on a sample of that region or on fundamental notions concerning human behavior” (Kohler and Parker 1986). The basic premise of predictive modeling is that human spatial behavior is to a large extent predictable, which implies that the locations where people lived and performed their daily activities can be identified on the basis of statistical and/or explanatory models.

Predictive modeling is used in archaeology for two purposes. First, it is a planning aid for cultural resource management (CRM) in order to assess the risks of disturbing archaeological remains during development projects. Second, predictive modeling is applied as a tool to develop and test scientific models of human locational behavior. In academic contexts, therefore, predictive models can be considered as heuristic tools (Verhagen and Whitley 2012) that can play an important role in formalizing and quantifying theoretical notions on the development of settlement patterns and land use.

Predictive models can be made following two different strategies, usually named “inductive” and “deductive” (Kamermans and Wansleben 1999), but more accurately described as “data driven” and “theory driven” (Wheatley and Gillings 2002). In “data-driven” modeling, the location of archaeological sites in a study region is compared with a number of parameters that are considered to be important to settlement location (such as slope gradient, soil type, or distance to water), using geographic information systems (GIS). The results of this quantitative site location analysis can then be extrapolated to areas where no archaeological data are available, and will thus result in a prediction of site

densities for the whole area studied. A popular technique for data-driven predictive modeling is logistic regression, but many more options are available, including ecological niche modeling, Monte Carlo simulations, and Bayesian statistics. However, despite the current state of sophistication of statistical modeling, it is still very difficult to state which statistical technique performs best, since there are hardly any case studies available where methods are compared.

The second, “theory-driven,” approach bypasses most of the statistical complexity by defining theoretical assumptions about the parameters influencing human spatial behavior. For example, it can be assumed that early farming communities preferentially located their settlements in environments well suited for agriculture and animal husbandry, which in turn can be related to parameters such as the abundance of certain soil types within a particular radius. Expert-based weights are given to the parameters included, and the resulting models are then compared to the known archaeological record in order to judge their performance. This approach has the advantage that it can include more sophisticated theoretical frameworks that are based on causal explanation, it can include human agency as a factor, and it is not directly dependent on archaeological datasets (Verhagen and Whitley 2012). Deciding on a best possible model, however, still implies comparing various parameter weights with the actual archaeological data.

The roots of predictive modeling can be traced back to the days of “new archaeology,” and in particular the development of site catchment analysis in the 1970s. Archaeologists became aware that human settlement is intimately linked to its environmental setting, which also implied that it should be possible to predict the locations suitable for human settlement. Around the same time, CRM developed in the United States in response to legislation aimed at the protection of cultural heritage. In the absence of sufficient data to identify all archaeological sites in a region, predictive modeling answered the need for a more comprehensive mapping of cultural resources. When GIS arrived on the

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scene in the early 1980s, it allowed for much more advanced computer-based mapping and modeling and paved the way for further proliferation of predictive modeling, initially in the United States (Judge and Sebastian 1988) and later also in Europe (van Leusen and Kamermans 2005). From the outset, predictive maps served two specific purposes. First, they were intended to influence the decision-making processes of planners and to convince them that developments should take place in the least-sensitive areas; and second, they were to guide the archaeological investigations once developments started, by making reasoned choices on where to concentrate research efforts within the constraints of available time and money. Since then, predictive modeling has been applied in numerous cases around the world. Its cost-effectiveness in CRM has been proven, and it has provided a basic degree of protection to zones of high archaeological potential in those regions where it is included in CRM policies.

Nevertheless, predictive modeling has encountered substantial criticism from archaeologists. This is because it will never be able to accurately predict all archaeological remains. The models are only as good as the data and theories that have been used to create them, since we can only extrapolate from the existing state of archaeological knowledge. In that respect, there is no real difference between theory-driven or data-driven approaches. For many archaeologists the risk of “wrong predictions” and their undesired consequences for the protection and investigation of the archaeological record in CRM is unacceptable. From a scientific point of view, however, discrepancies between prediction and data can be the starting point to develop new theories about site location and/or to direct future data collection practices, which could also be a guiding principle for decision making in CRM.

The potential flaws of predictive models were summarized by van Leusen and Kamermans (2005):

- The archaeological input data are usually not representative of the full archaeological record, and the archaeological record itself is a biased reflection of human activity in the past; therefore, we cannot expect that models based on existing archaeological datasets will

accurately predict all locations of past human settlement.

- The predictor variables used are often based on modern-day environmental datasets, which may not be at the right level of detail and accuracy for predictive modeling purposes, and may not accurately reflect the situation in the past.
- Sociocultural variables are usually not included.
- The temporal resolution of predictive models is limited, since this is determined by the archaeological and environmental input datasets used.
- Testing of predictive models is often done in a haphazard way, and in most cases does not involve a representative field survey; the distinction made between areas of low and high probability has instead often led to a policy of not surveying the low-probability zones, and in this way, a self-fulfilling prophecy will be created (Wheatley 2004).

Predictive modeling has often been criticized for restricting itself to a limited set of “environmental” variables. This can partly be attributed to the fact that there are relatively few relevant datasets available that cover large areas. The inputs most often used are derivatives of digital elevation models (in particular slope and aspect), and, to a lesser extent, topographical, geological, and pedological maps. This approach has been successfully applied in many cases, but the datasets are sometimes used in a very uncritical way. Sociocultural variables (such as distance to roads, or to specific archaeological sites), on the other hand, are much more difficult to implement in predictive models because of the scarcity of relevant data and lack of quantifiable theoretical models, although there is no inherent barrier to including them (see for example Whitley et al. 2010).

Ideally, the desired degree of accuracy of a predictive model should determine what is needed in terms of data and knowledge. In practice, however, predictive models are often made on the basis of data that happen to be available, and for this reason they can vary considerably in their accuracy. It is therefore extremely important that the models are tested, both internally in order to establish the uncertainties in the parameters and

archaeological data used by means of sensitivity analysis, and externally by adding independent, representative archaeological data. Establishing the representativeness of archaeological datasets, however, is often very difficult, since in many cases there is insufficient information about the intensity and methods of survey applied and about the influence of potential biases, such as the visibility of archaeological remains on the surface. These factors highly influence not just the number of archaeological sites found, but also the types of sites that can be discovered successfully (Verhagen 2008).

Creating and testing archaeological predictive models is therefore a complex exercise, at the end of which the results need to be translated into terms that can be easily implemented in CRM and other planning contexts. Formal statistical assessments do not necessarily play an important role in this. Instead, a number of explicit and implicit assumptions about the importance of specific archaeological remains, their state of preservation, and the costs of excavating them are used as well to assess the archaeological and financial risks of development plans. Thus, creating predictive models is only one stage in the decision-making process surrounding archaeology in spatial planning, and as such their role in CRM should not be overemphasized. However, since they are used at the beginning of the planning process and will direct decision making in subsequent stages, their accuracy should be a major concern to archaeologists, developers, and planners alike.

SEE ALSO: Bayesian Statistics; Heritage and Policy; Heritage Planning and Design; Sampling Theory; Spatial Analysis; Statistics and GIS

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FURTHER READINGS

Principal Component Analysis

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Principal component analysis (PCA) is one of a number of exploratory statistical techniques that can be employed to recognize, interpret, and present patterns in multivariate datasets. PCA is ideal for investigating relationships between variables and cases, as well as characterizing significant data trends that involve multiple variables (Baxter 1994; Madsen 1988; Shennan 1997). Generally, PCA is ideal for exploring continuous measurement-based data associated with artifact morphology, elemental composition, and, as shown in this entry, spatiotemporal contexts. Below we outline how PCA works as a method of analysis and summarize two published cases that use this method to elucidate archaeological patterning.

For the sake of introduction, imagine a dataset consisting of values for 14 different measurements taken from a sample of stone projectile points (blade length, blade width, stem length, stem width, thickness, etc.). A perfectly accurate representation of the relationships among the variables and cases in this dataset would require 14 dimensions; however, humans can only simultaneously visualize up to three variables at a time. PCA and related techniques, including correspondence analysis and multidimensional scaling, allow analysts to overcome this dimensional limitation through ordination—a method that reduces the number of dimensions required to represent the many relationships among cases and variables in a dataset.

PCA achieves this dimensional reduction by grouping together variables in the dataset that are correlated. In most archaeological applications, covariance is expressed as a matrix of

standardized correlation coefficients (r) for all variables, with values ranging between -1.0 and 1.0 (Baxter 1994, 65–66). PCA aggregates highly correlated variables together into summary variables called principal components (PCs). While each principal component is comprised of correlated variables, PCA requires that the principal components themselves be uncorrelated. When represented visually, these uncorrelated principal components can be seen as perpendicular (or orthogonal) axes that define a new space within which the variables and cases can be plotted with minimal loss of the original information (Shennan 1997, 281–282). PCA then determines new positions for variables and cases within this transformed space.

The technique provides powerful tools for exploring the relationships between variables and cases through a combination of numeric and visual results. There are three important and related types of numeric information calculated for each principal component—eigenvalues, component loadings, and component scores. An eigenvalue (or latent root) is most easily conceived of as the total amount of variation in a dataset accounted for by a particular principal component (Shennan 1997, 279). Eigenvalues themselves are difficult to interpret directly. Therefore, they must be transformed by dividing each value by the number of variables in the dataset and then multiplying by 100. The resulting value is the percentage of total variation in a dataset explained by that component. It is always the case that the first principal component will have the highest value, and subsequent components will be defined by decreasing eigenvalues (Baxter 1994, 67).

PCA results typically include a table listing component loadings for variables (rows) and principal components (columns). Component loadings are standardized measures of covariation between each principal component and each variable in a dataset and can be interpreted exactly like correlation coefficients (r) (Shennan 1997, 278). The analyst can determine which variables are most closely related to a particular

principal component by identifying the variables with strong positive or negative loadings. By squaring component loadings, the analyst can also determine what percentage of variation in each variable is explained by a principal component. These two procedures are essential for identifying and interpreting the data trends that are being marked by the principal components.

PCA also provides a table of numeric results called component scores relating cases (rows) to principal components (columns). Component scores can be thought of as translated coordinate values marking the position of a case along each of the principal components. Each component score is derived from the original variables by multiplying the standardized value of each case by the component loading of each variable and summing the results for all of the variables (see Shennan 1997, 285–187 for a detailed discussion). Analysts can best understand the data trends captured by principal components by examining cases with component scores at both the positive and negative ends of a principal component.

While the numeric results of PCA are crucial for identifying and interpreting patterns in multivariate datasets, the visual results of PCA are perhaps better suited for presenting those patterns to an audience. Visual representation of data is often the main goal of ordination methods like PCA; these are scatterplots that depict the relationships between variables and cases along axes representing the principal components. Typically, PCA results are presented as separate scatterplots for variables and cases, respectively. Because component loadings are used as coordinates for variables and component scores for cases, the scatterplots distill much of the data contained in the numeric results; spatial clustering of variables or cases suggests similarities. Additionally, because both cases and variables are plotted within the same relative principal component dimensions, the relationships between variables and cases can be represented spatially (Baxter 1994, 57–59). Looking at the paired scatterplots, *variables* occupying the same relative principal component space as a cluster of *cases* can be said to have significant influence over the observed similarities among cases in the cluster (Shennan 1997, 295–296). Scatterplots also allow the analyst the additional option of coding cases with different symbols to represent other dimensions,

such as time or space, which may aid in further understanding the data trends.

To demonstrate the utility of PCA with respect to archaeological data, we present two cases from the published literature. The first case highlights the efficacy of using PCA to quantitatively integrate seemingly disparate types of data: animal bone fragments and carbonized plant remains. Most often these two types of data are analyzed separately, which can create an artificial conceptual divide between the meat and vegetable portions of the diet (VanDerwarker and Peres 2010).

In their case study from Formative-period Veracruz, Peres, VanDerwarker, and Pool (2010) consider how sociopolitical status and contexts of discard vary with respect to plant and animal foodways at the multi-mound political center of Tres Zapotes. Based on architectural and artifactual analyses, Peres and coauthors were able to define three broad types of socioeconomic space: nonelite domestic space, elite households, and ceremonial areas. In analyzing how sociopolitical space varies in relation to food use, the authors begin by conducting independent analyses of the archaeobotanical and zooarchaeological datasets. Independent analysis of the plant data did not reveal much difference in plant presence or abundance between these three contexts; however, beans appear to have been restricted to elite contexts, and nonelite contexts appear to have had elevated levels of tree fruit remains. Independent analysis of the faunal data revealed a greater concentration of deer and dog remains in elite contexts versus fish and turtle remains in nonelite contexts. Patterning in ceremonial areas was less clear when compared to the elite and nonelite household areas.

In order to clarify the patterning in ceremonial areas, and in line with the idea that ancient food practices should be conceptualized as cuisine in which ingredients are combined to form distinct dishes, Peres et al. (2010) turned to PCA. To make the plant and animal datasets comparable, each dataset was standardized in a similar manner. Frequencies of plant fragments were summed by type (maize, fruits) for each context (nonelite, elite, ceremonial), and each sum was then divided by the total plant weight in that context. Likewise, animal bone frequencies were also summed by type (deer, dog, fish, turtle), and

divided by total bone weight for each context. The resulting continuous data were then used in the PCA. The integration of these datasets revealed patterning that was not apparent through the independent analyses alone. Both plant types (maize, fruits) mapped directly onto nonelite domestic contexts, with values that did not overlap with the elite or ceremonial contexts. Given that maize was present in similar frequencies across all three contexts in the independent analysis, the fact that the PCA results associate maize specifically with nonelite contexts suggests that plant food frequencies in elite and ceremonial contexts were overwhelmed by a much higher frequency of meat resources. Thus, the PCA reveals that the nonelite diet was focused almost entirely around plant foods, with meats being preferentially incorporated into elite diets and ceremonial events. Such an interpretation would have been impossible without integrating these datasets using PCA. While this case employs subsistence data, any type of material data could be incorporated, with the caveat that all data used in the PCA are transformed into continuous data and standardized in similar ways to make them comparable.

PCA is also useful when trying to determine spatial clustering of multiple variables. In order to be appropriate for this type of analysis, the cases must represent discrete spatial contexts (e.g., features, units, houses). The case study we use to exemplify PCA as a tool of spatial analysis is a burned house structure from the Ravensford site (ca. 1700–1830 CE), located in western North Carolina (VanDerwarker, Alvarado, and Webb 2014). The structure was excavated in a series of contiguous 1×1-m units, totaling 69 units. Given the details of timing, burning, and house abandonment, the plants recovered from the floor of this structure relate to activities that occurred within it toward the end of its use-life. PCA was thus used to determine how the structure's ancient inhabitants organized food storage and processing tasks.

VanDerwarker and colleagues (2014) use the 1×1-m excavation unit as the spatial unit, in which each unit represents a single case in the analysis. The variables are represented by the plants that were identified in those units, and all plant frequencies were standardized to total plant weight for each respective excavation unit.

The first PCA run identified several units that formed two distinct clusters. The first cluster was represented by a single unit located near the southern corner of the structure. The second cluster included five contiguous units in the northwestern area of the structure. In order to determine additional patterning, a second PCA was conducted after excluding the units from clusters identified in the first analysis. The second run resulted in one additional unit being included in cluster 1, one additional unit being included in cluster 2, and a third unit creating a new cluster (cluster 3).

Based on the spatial clusters defined through the PCA, the authors were able to interpret how interior food storage and processing were organized within the house. Cluster 1 was composed mostly of nutshell and maize remains, suggesting that the southern corner of the structure was an area dedicated to staple food processing. Cluster 2, located in the northern corner of the structure, was dominated by fruit seeds and interpreted as an area of dried fruit storage. The authors suggest that fruits were dried and then placed in storage by hanging them from ceiling rafters. When the house burned and the roof collapsed, these fruits likely fell to the floor amid a background of general food-processing debris. Cluster 3, in the west-central area of the structure, was dominated by bottle gourd rind and seed fragments. Bottle gourds were primarily used as liquid storage containers and were probably suspended from the rafters, much like the dried fruits. When the roof beams collapsed during the structure's incineration, the gourds would have crashed to the floor and shattered, littering the floor with a high density of bottle gourd rind fragments. This example demonstrates how PCA can be employed to define clear activity clusters in situations where material remains represent abandonment debris or primary refuse.

Complex multivariate statistics like PCA can seem daunting to the quantitatively challenged archaeologist, but PCA's utility in dealing with large datasets to reveal novel patterning is clear. The cases above exemplify the interpretative power of PCA to move us beyond what we can learn from simple univariate analyses. PCA is thus an important technique to curate in our toolkit of archaeological data analysis.

SEE ALSO: Cluster Analysis; Compositional Data Analysis; Computer Applications in Archaeology; Correspondence Analysis; Factor Analysis; INAA and Material Analysis; Inferential Statistics; Instrumental Analysis of Lithics; Neutron Activation Analysis (NAA); Statistics in Archaeology

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Quantum Analysis

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The study of the origins and evolution of systems of measurement (a discipline referred to as historical metrology) has attracted both scholars and amateurs who share an interest in discovering mathematical patterns—the bygone analogues of our pounds and kilograms, yards and meters, and quarts and liters. Determination of the absolute values of the standards underlying early systems of measurement is a fundamental task of historical metrology. Empirical studies are based on two classes of evidence: *metrical artifacts* that provide primary or direct evidence, for example, balance weights, rulers, and standardized containers for liquid and dry measures manufactured according to specific desired volumes; and *products fashioned according to standard units of measure* of mass, length, and volume, for example, ingots, architectural spans, and certain clay vessels, whose relevant metrical dimensions reflect rational and practical series that are useful in evaluation, accounting, and design. These items might constitute secondary or indirect lines of evidence. Clearly, the credibility of any argument for metrical configuration of either class of data will be a function of sample size. Inasmuch as both of these lines of evidence derive from surviving material remains, they invite archaeological inquiry. To the extent that systems of measurement are tools of industry and of trade, moreover, they can provide a window into understanding economic and political relationships.

Scholars have traditionally focused on weight metrology, since identifiable balance weights often survive to their original or approximate target masses (depending on their material and preservation). Their masses can be determined quickly, and the corpus of published balance weights with reliable and precise archaeological contexts is constantly growing, permitting us to address interesting questions about economics,

trade, design and aesthetics, and cultural and political relationships in antiquity. The mathematical structures of these systems are windows into understanding the origin and evolution of quantitative thought, since they are proxies for pure number, witnesses to how early peoples quantified their raw materials and finished goods. Since much recent scholarly effort has focused on modeling ancient measurements in the data-rich eastern Mediterranean, that region will provide the primary example for this entry.

History of research

Early attempts to isolate standards of weight in early societies empirically—that is, by weighing identifiable well-preserved balance weights that are arguably close to their originally intended masses, as well as items presumed to have been manufactured to targeted masses—were based on recognition of ratios of mass relating balance weights found on individual archaeological sites, and later comparing those results over broad regions. The general assumption was that the ratios expressed simple series of denominations. Multiples of a one-unit standard might run in one or more of the following series:

2, 4, 8, 16, 32, ... (binary)

5, 10, 20, 25, 50, 100, ... (decimal)

3, 6, 12, 15, 20, 30, 60, 120, ... (sexagesimal)

Smaller denominations have typically included simple unit fractional quantities, including $\frac{1}{2}$, $\frac{1}{4}$, $\frac{1}{8}$, ... , doubtless because doubling and halving are the quickest and most precise activities to execute on a double-pan balance. Other unit fractions (notably $\frac{1}{3}$) are attested, and when precision in accounting demanded it, non-unit simple and useful fractions were generated, including $\frac{2}{3}$ and $\frac{3}{4}$, as well as fractions with denominators 5, 10, and 12, inter alia. As a rule, we may expect numeration and metrology in ancient systems to have been relatively uncomplicated, and to reflect the same ease of use that characterizes everyday

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counting and measuring in our day. The empirical evidence indeed bears this out. Thus, recovering the mathematical structure of an ancient system ought to be a relatively straightforward, common-sense exercise in arithmetic, and indeed much progress has been made on decoding ancient systems using nothing more than intuitive trial-and-error, goodness-of-fit approaches.

Case studies

In a few cases, inscriptional evidence exists in the form of numerical symbols and/or words incised in balance weights and other artifacts in the primary/direct category that designate their values within a system. The present author demonstrated the value of such markings in the case of balance weights from Greece, Crete, and the Cycladic islands in the later Aegean Bronze Age, ca. 1900–1200 BCE (Petruso 1992). Among more than 200 specimens identified as balance weights, about a quarter of them show simple markings. Most of the inscribed specimens (primarily discs of stone or lead), including many that are unmarked, leave no doubt that the most commonly attested Bronze Age Aegean weight system was based on a unit standard in the vicinity of 60–65 g. Simple dots, circles, and strokes borne by these artifacts suggest multiples in a primarily duodecimal structure (1, 2, 3, 4, 6, 8, 12, 24) and unit fractions $\frac{1}{2}$, $\frac{1}{3}$, $\frac{1}{4}$, and $\frac{1}{8}$, although $\frac{2}{3}$ and $\frac{3}{2}$ are also indicated. Notably, each of two 24-unit weights excavated from two Minoan Cretan palaces bears two large and four small circles (to be read “two tens, four ones”, as their masses confirm), indicating a decimal base for numeration. Both Linear A and Linear B Aegean scripts were primarily tools of inventorying and accounting. Not surprisingly, weighing also demonstrably functioned on a base-10 system.

The best-known example of an exercise in historical metrology is the long-term project of Oxford engineering professor Alexander Thom (d. 1985), who made thousands of precise linear measurements over many years at Stonehenge and many other stone circles in the British Isles with a view to determining whether they were designed and constructed according to standard spans. For the purpose of introducing the

analyses that follow, a unit standard (or as it became known, a *quantum*) might be represented mathematically by the simple equation:

$$X = Mq + \epsilon \quad (1)$$

where X is the value of an observation on a metrical scale (e.g., feet, grams, cubic centimeters), M is an integer, q is the quantum on which the system is based, and ϵ is an error term that can be positive or negative.

The data suggested to Thom a repeating span of 0.83 meters (2.72 feet), which he labeled the “Megalithic Yard,” and its double, 1.66 meters (5.44 feet) (Thom 1955). He refined and defended his argument subsequently for three decades. Although scholars have long been intrigued by the possibility that architectural units of measure existed over a wide region and many centuries, Thom’s arguments inspired scant consensus, and today have few adherents.

In the same year that Thom published his megalithic yard analysis, S. R. Broadbent (1955) introduced an explicitly quantitative approach to isolating candidates for standard units in a disparate population of data. He defined a “quantum hypothesis” test:

$$y_i = \beta + 2r_i\delta + \epsilon_i \quad (\text{for } i = 1 \text{ to } N) \quad (2)$$

where β and 2δ are constants (2δ is the quantum), r_i is zero or a positive integer, and ϵ_i is the error of observation. His goal was to develop a means to analyze groups of observations that were either known or suspected to have been quantally configured. In this, he sought an objective method for identifying particular quanta rather than simply testing chosen candidates for goodness-of-fit.

The most abiding contribution to date with respect to methodology in ancient metrology, however, was proposed by Oxford mathematician D. G. Kendall (1974). He chose a subset of the rich database of megalithic measurements amassed by Thom, namely the diameters of 169 ancient stone circles in Scotland, England, and Wales. Kendall developed the following equation:

$$\phi(q) = \sqrt{\frac{2}{N}} \sum_{j=1}^N \cos(2\pi\chi_j q) \quad (3)$$

where $\phi(q)$ is a “score” of the likelihood that a tested quantum X was the standard on which

the system was constructed; N is the number of specimens; and $\sqrt{\frac{2}{N}}$ is a scaling factor based on the population size.

The introduction of Kendall's "cosine quantogram" (Kendall 1974, Figures 4 and 5) was a significant step in the evolution of historical metrology. It obviates the inclination of the researcher to argue for a particular standard on the basis simply of goodness-of-fit. Rather, iteration of the function tests very many possible candidates over a continuum from relatively small to about half the value of the largest observation in the dataset of N observations. The computer-generated graphic output is easily comprehensible and permits rapid identification and ranking of potential quanta.

The procedure has great utility. Each $\phi(q)$ is either positive or negative in sign for a given quantum candidate. Negative scores are rejected, and only relatively high positive scores merit further consideration. The higher the score, the greater the likelihood that the associated value might have been the quantum—or one of the quanta—on which the system was based, rather than simply randomly distributed. Kendall's analysis of the megalithic circles confirmed that a value of 5.44 feet was indeed prominent in Scotland, but as a measure for British megalithic architecture overall, it was not found to be statistically compelling.

John F. Cherry (1983) was the first to apply the cosine quantogram procedure to advantage with respect to another purported ancient linear measure, namely a "Minoan foot" on which the design and construction of the Cretan Bronze Age palaces had been proposed.

Recent research

The cosine function defined by Kendall has gained broad acceptance by archaeologists. Cemalettin Pulak (1996) put it to good use in his metrological analysis of an extraordinary corpus of balance weights from two Late Bronze Age merchant shipwrecks (ca. 1300 and 1200 BCE) excavated off the south coast of Turkey in the 1960s and 1980s. More recently, scholarly interest in the quantal search procedure has evolved to the point where the method itself is now receiving

scrutiny. Edward Castle (2000, 128–40) and Jari Pakkanen (2011, 143–66), who have focused on populations of both ancient balance weights and linear spans, are concerned *inter alia* with, respectively, the relationship between sample size and the reliability of the highest-scoring tested quanta returned in analyses, and the ability of Kendall's function to isolate two or more standards in a population of observations. The directions of this research promise to refine the precision of future quantum analyses as well as the plausibility of interpretations, especially for those societies that employed multiple unit standards.

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R Coding and Modeling

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Introduction

R is a programming language and computing environment useful for statistical and geospatial analysis, data visualization, and mapping. It is significant as the most widely used scientific programming language in archaeology. This entry will briefly describe the origins of R and survey its distinctive features, including how it enables reproducible research. It will also highlight some current uses of R in archaeology, and suggest some possible future directions.

R was originally developed in New Zealand in the early 1990s as an academic research project to create a language for introductory data analysis courses. It is closely related to the S language and S-PLUS software. Currently it is maintained by an international community of about 20 computer scientists and statisticians, and has six-monthly update cycles to the core libraries. It is widely used in academia, especially statistics and social sciences, and in industry. R has a vibrant online community that is friendly to novices, as well as numerous informal user groups, an annual conference (useR!), a non-profit organization (R Foundation), and a peer-reviewed journal (*The R Journal*).

Distinctive features of R

R differs from other software commonly used for data analysis in two important ways. First, R is an open-source software program. This means that, unlike commercial data analysis software (e.g., SAS, Stata, SPSS, JMP, SigmaStat, etc.), R is free for anyone to download and install (cf. PAST, JASP, and PSPP). The full details of all its algorithms are publicly available for inspection and modification (cf. JASP and PSPP), unlike

for many other programs where these details are not available to the user (cf. PAST, and all commercial software). Second, for many archaeologists a spreadsheet program such as Microsoft Excel is their primary tool of data analysis and visualization. The primary mode of interaction is by manipulating cells in the spreadsheet, and through mouse-clicks to access commands in the drop-down menus. R differs from all other statistical software because it is not a spreadsheet program and has very few mouse-driven actions. Instead, R has a prompt to which typed commands are interactively sent to the R interpreter.

As a programming language, R gives the user great flexibility through access to a vast variety of methods. The user is not limited to built-in functions, but can easily create new ones. The R interpreter evaluates commands typed by the user, and the computed output is printed to the screen or stored for later use. These typed commands are saved in a plain-text R script file, which becomes a record of all the steps in a data analysis.

Unlike most other software, R also has an environment. Any type of data file (e.g., Excel, CSV, OBJ, TIFF, JPEG, shapefiles, netcdf, etc.) can be imported into the R environment and manipulated, analyzed and combined with other data using a coherent and integrated set of operations.

After a data file is imported into R, it is usually represented as a vector (a one-dimensional set of values of the same type, i.e., numeric, character, logical, etc.) or combinations of vectors. A frequently-used data structure in R is the data frame. This is analogous to a table of data in a spreadsheet, and formally in R is a list of different types of vectors of equal length. Many functions (named sections of code that perform a specific task) in R are optimized for working with data frames, and can perform summary statistics and complex operations very quickly on these structures. Related structures include the matrix (vectors of the same length but only one type, equivalent to a table of only numbers or only characters, cf. the standard structure for MATLAB software), and the list (a vector that

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combines elements of any data type). Lists are complex, hierarchical objects (a list can contain lists) that are frequently used during looping operations to automate complex actions efficiently for many items (e.g., hundreds of Excel files need to be read and computed on).

R is primarily a functional programming language, which means that the basic unit of activity when using R is typically the evaluation of mathematical or computational functions. The basic installation of R contains over a thousand functions. In addition to these built-in functions, an R user can install over 10,000 packages of more specialized functions freely contributed by R users. These packages are distributed via three major online code repositories: Comprehensive R Archive Network (CRAN), Bioconductor, and GitHub. Some examples of add-on packages specifically for archaeologists include *archdata* (contains 11 archaeological datasets from around the world reported in published studies), *FedData* (automates downloading of geospatial data from several US and international federated data sources), *zooaRch* (analytical tools to make inferences on zooarchaeological data), and *recexcavAAR* (functions for 3D reconstruction and analysis of archaeological excavations, including methods to reconstruct natural and artificial surfaces based on field measurements).

In recent years a collection of R packages known as the tidyverse has emerged as a major new direction for the R language (Wickham and Grolemund 2016). These packages share common philosophies of tidy data, which is an approach to representing and manipulating data where variables are in columns, observations are in rows, and values are in cells. Tidyverse packages are designed to work together, with common data representations and simple, consistent programming interfaces for fast, efficient data analysis and visualization. For an archaeologist learning R for the first time, the tidyverse approach and packages are an ideal starting point.

Reproducible research using R

In many areas of social science there is an emerging concern to improve the reproducibility of published results. Reproducibility is the

cornerstone of science, and often defined as the ability to recompute the results of a data analysis, given a dataset and information about the data analysis pipeline (Marwick 2017). One contributor to this crisis is the use of mouse-driven software such as SPSS, where many steps of the analysis pipeline are not preserved in a convenient form, or at all. This makes it difficult to reproduce results obtained by pointing-and-clicking. Using R is one aspect of solving the problem of irreproducible results. When data are analyzed using a programming language such as R, the saved R script file contains a full record of every decision made during data analysis, and can be shared with other researchers.

In addition to scripting every step of the data analysis, R also integrates with several other technologies to enable reproducible research. R code can be written among narrative text using the R Markdown text formatting system. Markdown is a simple, easy-to-learn, open-source language for formatting documents. This means that entire journal articles and theses can be written in R Markdown, with code and text interwoven together in the same document (Figure 1). Using the Pandoc program (included with RStudio), the R Markdown document can be executed, or rendered into a standard format such as PDF or Microsoft Word, so that the R code is run and the figures and tables for the manuscript are generated and inserted in place in the output documents.

The significance of this use of R in manuscript preparation workflow is that it avoids the typical practice of copying and pasting output from a statistical software program (e.g., SPSS) into a word-processing program (e.g., Word). Copying and pasting separates a result from the steps that generated it, making it impossible to trace the decisions made during an analysis. Copying and pasting is also error-prone because mistakes or ad hoc, undocumented modifications to output can be introduced to the text during revision cycles. R Markdown provides a simple convenient workflow for writing code and text to easily reproduce the results of a data analysis.

Another advantage of using R and R Markdown is that the data analysis pipeline behind an article or thesis can easily be shared with other archaeologists by sharing the R Markdown documents that generated the output document. This

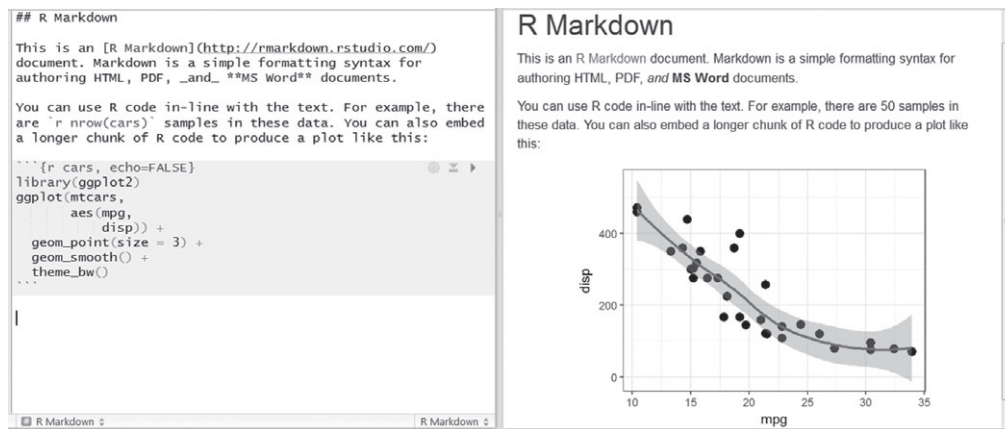


Figure 1 A screenshot from the RStudio program showing how R can be used for reproducible research. In the left panel is a text editor, where we write plain text and code in an R Markdown file (known as a Rmd file). In the right panel is the output that is produced when the Rmd file is “knit,” or rendered, into a document. In this example, the Rmd has been knitted to produce a HTML file, but we could also produce a PDF or Microsoft Word document from the same Rmd file. The first paragraph of the text in the example demonstrates how to use markdown for basic text formatting (e.g., a heading, a URL, bold and italic text). The second paragraph shows how R code can be embedded inline in the text. The rendering process automatically runs the code and inserts the result in the text; here, it computes the number of rows in the “cars” dataset and inserts the result (50) in the rendered document. The text in the gray region on the left is a chunk of R code that produces the plot in the HTML file on the right. We use `echo=FALSE` in the code chunk to specify that the code chunk is not displayed in the HTML file; we see only the plot that the code generates. This method of writing text and code in the same document enhances reproducibility because the methods of data analysis (i.e., the R code) are explicitly included in the same document as the text, and the code can be easily and repeatedly run to generate results. This removes the need to copy and paste tables and plots from other software into the text, eliminating transcription errors and confusion about where a particular result came from.

is important for scientific archaeology because it enables more efficient adoption of new methods, and more rigorous checking of new results to establish their correctness. Furthermore, an archaeologist using R who does not make their code openly accessible upon publication is missing an important opportunity to increase the visibility and impact of their research.

A related tool that is often used with R to improve the transparency of data analysis is Git, the free and open-source version control system. Using Git with R means that researchers can track changes they make to their code and text files. Each decision point can be recorded, even if it is later deleted from the final document. Git allows collaborators to compare versions of code and text, retrace errors, explore new approaches in a structured manner, while maintaining a full audit trail. Several free web services have

user-friendly tools for collaborating in the open or privately with code and documents written with R and Markdown that are tracked using Git (e.g., GitHub, GitLab, BitBucket). The `rrtools` package at <https://github.com/benmarwick/rrtools> (Marwick, Boettiger, and Mullen 2017) includes instructions, templates, and functions for making a basic compendium suitable for doing reproducible research with R, Git and other related tools.

Current uses of R in archaeology

R’s flexibility as an analytical tool means that it is currently used by archaeologists for a wide variety of applications. An online “task view” page at <https://github.com/benmarwick/ctvarchaeology> contains an annotated list of R

packages relevant to archaeological research. Specialist studies of typical archaeological items such as stone artifacts, animal bones, isotopes, and sediments have all been done to publication quality entirely with R. R has also emerged as the tool of choice for several computationally intensive subspecializations in archaeology.

Archaeological modeling in R

Archaeological modeling in R means representing archaeological data for a purpose. This means that the data stand for something in the real world, such as past human behaviors or site formation processes. The purpose is often to gain new insights into the relationships between observed variables and their possible behavioral and environmental correlates. Statistical modeling in R takes archaeological data and combines it with model formulae, equations, uncertainty and randomness to test hypotheses about how the system being modeled actually works. For any kind of modeling, from linear regression to exotic machine learning method, R is ideal for identifying patterns in data, classification, untangling multiple influences, and assessing the strength of the evidence. In R, a statistical model is often expressed with formula notation, for example $y \sim x$. This can be read as “ y is modeled as a function of x ,” where y is a response variable whose content we are trying to model with x , called the explanatory variable. Following this notation, a typical linear regression model in R will look similar to this `fit <- lm(y ~ x)`, which is the R code for the traditional mathematical representation of $y_i = \beta_0 + \beta_1 x_i + \epsilon_i$.

This formula notation is the starting point for most models in R, including ones where explanatory variables are continuous, categorical, or a mixture of both, and when the response variable is a continuous measurement, a count, a proportion, or a category. The types of variables involved determine the type of model used. Typically where explanatory variables are continuous, regression models are used; when they are categorical, analysis of variance (Anova) is used; and when they are both continuous and categorical, analysis of covariance (Ancova) is used. For the response variable, when it is continuous we can

use normal regression, Anova, and Ancova; when it is a proportion (i.e., continuous but within the range of 0–1) or binary (i.e., 0 or 1) we use logistic regression; and when it is a count we use log-linear models. For each of these variations, only minor modifications to the fundamental $y \sim x$ R code are necessary.

Working with radiocarbon dates is a common task for many archaeologists, and although several specialized software tools exist solely for this purpose (e.g., OxCal, BCal), R has established itself as part of the toolkit for innovative analyses of radiocarbon dates. New methods of analyzing sets of radiocarbon dates to model population dynamics have been developed by several R-using archaeologists. Another area where R has become established as the dominant tool is in studies of cultural evolution. In this context, R has been used to model transmission of cultural information, and test hypotheses about population structure and dynamics. Similarly, spatial analyses from hemispheric scales to intra-site scales often use R for modeling archaeological and climate data with a location component. R is also used for zooarchaeology, geoarchaeology, agent-based modeling, and predictive site location modeling in academic and commercial archaeological settings. These more specialized applications are enabled by R packages contributed by researchers and programmers in other disciplines, such as Quaternary science, ecology and evolution, and geography.

A unique characteristic of using R for specialized archaeological applications is that it provides a complete toolkit, not just for the exotic methods, but also for generic activities surrounding the core analysis, such as importing, cleaning, arranging and exploring raw data, testing hypotheses, and visualizing the output with maps and plots. Using R at every step of the research process improves efficiency because it minimizes context switching and manual handling, which may also accidentally introduce errors and confusion.

Future directions

For archaeologists, R has emerged as a universal toolbox with which any kind of data analysis is possible. In addition to the more than 10,000

packages of R functions contributed by users, we can freely write new functions and packages to implement new methods. However, perhaps the most valuable and unique attribute of R is that when writing R code to analyze data, we create an enduring record of all the decisions made during a research project. This record, that is, the R code files, can be archived at a DOI-issuing online repository (e.g., tdar.org, osf.io, figshare.com, zenodo.org). This means we can easily find and reuse it in the future, and we can cite our R code in our publications (Eglen et al. 2017). With our R code freely downloadable from a trustworthy repository, readers of our publications can download and use the R code that generated the results reported in the paper. This is important for the advancement of archaeology because it allows for more complete review of published research, and so a more robust evaluation of its reliability. It also allows for more efficient and rapid transmission of new methods through the research community.

SEE ALSO: Archaeological Sciences; Archaeology; Artificial Intelligence; Bayesian Statistics; Chi-Square Analysis; Cluster Analysis; Compositional Data Analysis; Computer Applications in Archaeology; Correspondence Analysis; Databases in Archaeology; Dating in Archaeology; Descriptive Statistics; Distance and Data Transformation; Exploratory Data Analysis (EDA); Factor Analysis; Geometric Morphometrics; Human Skeletal Data Quantification; Hypothesis Testing; Inferential Statistics; Information Modeling; Linear Models; Lithics Data Quantification; Mathematics; Multivariate Analysis; Neural Networks; Parallel and Distributed Computing; Predictive Modeling; Principal Component Analysis; Radiocarbon Calibration and Age Estimation; Regression and Correlation Analysis; Seriation;

Simulation Modeling; Spatial Analysis; Statistics in Archaeology; Supervised Pattern Recognition

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Radiocarbon Calibration and Age Estimation

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Radiocarbon dating is one of the most widely used methods to provide age estimates for archaeological material. The method is most often applied to organic material, but in principle it can be used to date any carbonaceous material where the carbon is drawn from a reservoir which contains radiocarbon. Critical to the application of dating in archaeology is the selection of suitable material that relates closely the archaeological events under consideration.

Radiocarbon measurement

Determining the radiocarbon isotopic ratio ($^{14}\text{C}/^{12}\text{C}$) is a multistage process. The first stage is the extraction of chemical components of the sample that are original to the material being dated and free of any contaminants. For archaeological samples where there are a number of possible contaminants, this can be technically complex, and is normally carried out by laboratories that specialize in these types of material. The actual measurement of the radiocarbon isotope ratio can be made using a number of different technologies: originally, methods based on decay rate counting were used, but the majority of measurements are now undertaken using accelerator mass spectrometry (AMS). Corrections are made for mass-dependent fractionation by measurement of the stable isotope $^{13}\text{C}/^{12}\text{C}$ ratio, and for background levels, and the results of such measurements are either reported in terms of fraction modern ($F^{14}\text{C}$) or converted to a nominal conventional radiocarbon age estimate using Libby's original half-life estimate of 5,586 years (Libby, Anderson, and Arnold 1949). The activity of a modern sample is defined as that which a

natural sample would have had in 1950 had there been no fossil fuel effect, and is estimated from measurements on wood from 1850. In practice, all measurements are made relative to standards with precisely known characteristics. The radiocarbon age, A , is expressed in units of years before present (BP), which in this case means before 1950, and is a simple scaled logarithm of the fraction modern, F :

$$A = -8033 \ln(F)$$

This would give the true age of the sample if the amount of radiocarbon in the atmosphere had always been the same as that estimated for the natural atmosphere in 1950 and if the half-life was 5,586 years (Stuiver and Polach 1977). Neither of these is the true, and so the radiocarbon age is best thought of as a convenient logarithmic equivalent to the fraction modern which gives an order of magnitude estimate of true age.

Radiocarbon reservoirs

To use radiocarbon as a precise dating technique requires a detailed record of how radiocarbon has changed in the atmosphere (or other related reservoirs) over time, and to do this requires material that has been dated by other methods. For the Holocene and Late Glacial periods, wood dated by dendrochronology is used, which is ideal because it can be dated to the year and the carbon in wood is directly drawn from the atmosphere through photosynthesis. For earlier periods, a number of different archives are used, including uranium-series dated corals and speleothems, along with marine and terrestrial records. There are estimates for the levels of atmospheric radiocarbon covering the last 50,000 years (Reimer et al. 2013). From the 1950s onward there are also direct atmospheric measurements.

Radiocarbon is mostly generated in the upper atmosphere and becomes incorporated into the global carbon cycle, entering the biosphere through photosynthetic fixing of CO_2 . The mixing rates are such that the radiocarbon in

the atmosphere is fairly constant within each hemisphere, with a slightly lower level (about 0.5%) in the southern hemisphere (Hogg et al. 2013) because of the much larger ocean surface. Terrestrial plants within each hemisphere fix this radiocarbon directly, and so short-lived plants mirror the values found in the atmosphere (albeit with isotopic fractionation), and animals feeding on these plants or higher up the food chain do the same but with some time-averaging, which depends on the tissue concerned. Such effects are usually of the order of a decade or less and are often ignored. Woody plants lay down cellulose over time, and so, for example in trees that have annual tree rings, each ring reflects the prevailing atmospheric radiocarbon level when it grew. When you come to date wood, this can give a very significant “old wood effect,” which needs to be considered in the interpretation.

Through exchange with the atmosphere, radiocarbon is also incorporated into the oceans, but here the mixing rates are much slower and so different bodies of water have very different levels of radiocarbon. The surface oceans on average are about 5 percent (or 400 years) depleted relative to the atmosphere (Reimer et al. 2013), but different regions are affected by ocean upwelling, freshwater runoff, and other effects. In some cases, the offset between the local ocean and marine ocean average (ΔR) can be estimated by looking at paired marine and terrestrial samples (Stuiver and Braziunas 1993), but these offsets are likely to be variable in time and are not available for some regions. These additional uncertainties mean that radiocarbon dating of marine organisms is almost always less precise.

Rivers and other freshwater systems exchange CO_2 with the atmosphere. However, this is mixed with carbon from other sources, including that from detrital carbon in soils, which is depleted in radiocarbon compared to the atmosphere, and dissolved carbonate from the underlying geology (usually virtually free of radiocarbon). This has implications for dating material from fluvial systems and for the radiocarbon dating of speleothems in caves. In practice, it is usually necessary to undertake a local case study to determine such effects.

For humans and other omnivores there is the additional complication that they can, in some cases, source their food from a combination

of terrestrial, marine, and freshwater sources. To account for this, where it might be relevant, requires a detailed dietary analysis as such offsets can be significant (Fernandes, Meadows, and Dreves 2015).

The calibration process

In order to use a radiocarbon measurement for age estimation, we have to calibrate it against known-age material from the relevant reservoir. The first stage in any calibration is therefore the choice of reservoir. Agreed calibration curves are published by the IntCal group (see IntCal Special Issues in the journal *Radiocarbon*.) and cover the three best understood and most widely applicable reservoirs: the atmosphere of the northern hemisphere (currently IntCal13; Reimer et al. 2013), the southern hemisphere atmosphere (SHCal13; Hogg et al. 2013), and the oceans (Marine13; Reimer et al. 2013). These curves give the expected radiocarbon age as a function of true age over the last 50,000 years based on a compilation of different datasets.

Conceptually, the process of calibrating a single sample involves considering each possible year the sample might be from and comparing the measured radiocarbon for the sample to that of the calibration curve estimate for that year. The closer the two values are, the more likely the sample is to be of that age. The mathematical formalism used assumes normally distributed errors, and so strictly is better defined in terms of F^{14}C rather than radiocarbon age. If the radiocarbon calibration curve is defined as a function of time with a standard uncertainty $r_c(t) \pm \sigma_c(t)$ and the sample has a corresponding measurement given by $r_s \pm \sigma_s$ then the likelihood of any date t is proportional to:

$$\frac{\exp\left(-\frac{(r_s - r_c(t))^2}{2(\sigma_s^2 - \sigma_c^2(t))}\right)}{\sqrt{\sigma_s^2 - \sigma_c^2(t)}}$$

The probability density distribution is normalized so that the integrated probability over the full range of the curve is one. Note that the calibration process is independent of the half-life of radiocarbon. It is often useful to express the calibration

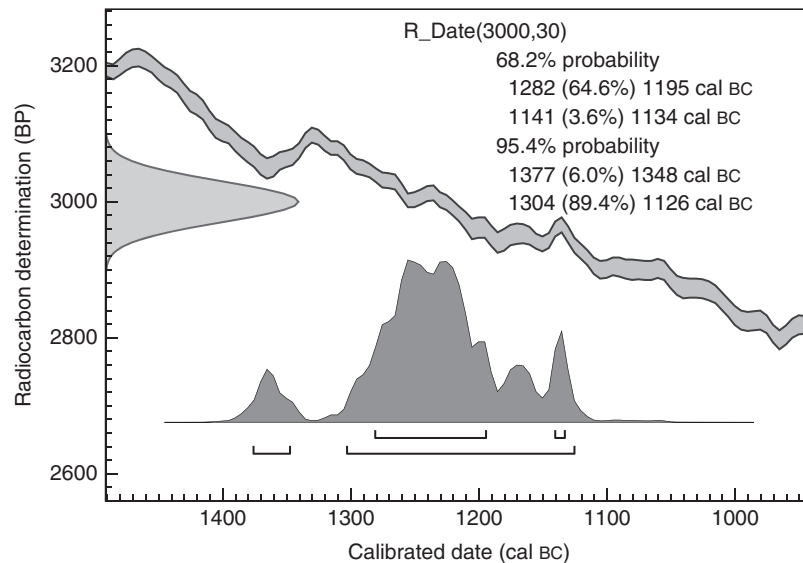


Figure 1 Example calibration diagram. The normal distribution on the left shows normal probability distribution associated with radiocarbon determination 3000 ± 30 , expressed in radiocarbon years BP on the y-axis. The calibration curve is shown at $\pm 1\sigma$ as a function of true age on the x-axis. The probability distribution shows the likelihood that the sample is of any particular age. Ranges are given at two different probability levels: for example, there is a 95.4 percent probability that the sample dates to between 1377 and 1126 cal BCE.

as a range and usually this is given as the highest probability density (HPD) range—either at 95 percent or 68 percent to be equivalent to the one and two standard deviation ranges for a normal distribution. The 95 percent range is usually considered to be the most useful, as it is unlikely (<5%) that the date lies outside this. The 68 percent range gives the “most likely” date range. For single date calibrations, it is not considered useful to use the mean and standard deviation, as the distributions following calibration are often multimodal and not normally distributed. Date ranges after calibration are usually expressed in the form of cal BP (where the year 1950 is 0 cal BP), cal AD, cal BC, cal CE, or cal BCE.

Software is available for performing the calibration process, including the widely used CALIB (<http://calib.org>) (Stuiver and Reimer 1993) and OxCal (<http://c14.arch.ox.ac.uk/oxcal.html>) (Bronk Ramsey 2009) packages. Figure 1 shows an example calibration diagram using OxCal. Note that the ranges, as in this case, can be split into several subranges because the probability distribution is multimodal.

Calibration of single samples can take account of offsets from the reservoir level, most commonly in the case of marine samples with a local oceanic ΔR offset (Stuiver and Braziunas 1993). Allowance for mixed reservoirs can also be made when calibrating dates from humans with a mixed terrestrial and marine diet.

Analysis of multiple dates

When there is more than one radiocarbon date to be used for age estimation, it is possible to take into account other information using Bayesian statistical approaches (Buck and Millard 2004; Bronk Ramsey 2009). The types of information that are included in such analyses include samples that share the same age, samples from the same period, and constraints on relative age. In some circumstances, such as lake sediments, we might also have information on the sedimentation process. In the Bayesian approach, this information is included as *prior* probabilities, the radiocarbon measurements themselves are the *likelihood*,

and from these the *posterior* estimate, which includes all information, can be derived. Bayesian chronologies are often site-based, making use of the physical stratigraphy, but they can also be based on regional cultural assemblages or constrained with historical information from written sources.

SEE ALSO: Dating in Archaeology

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Regression and Correlation Analysis

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Observing and establishing the relationships between variables is one of the most important tools for scientific research in general, not only in archaeology. Regression and correlation analyses are the statistical methods that are used for this task and belong to descriptive statistics (see DESCRIPTIVE STATISTICS).

Regression, correlation, and interpolation are concerned with the relationship between two or more variables. A correlation measures the degree of dependency of two variables. While correlation establishes a degree of relationship, it does not specify the kind of relationship; this is the aim of regression. A regression is the quantitative description of the relationship using a mathematical function. Interpolation estimates the value of a dependent variable based on an independent variable and usually uses regression techniques.

Both regressions and correlations deal with dependencies, themselves one of the main concerns of data analysis and statistics. The general idea is that the relationship between two variables reveals the relationship between the entities of the real world of which the variables are characteristic. If something (A) causes something else (B), the variables a and b should correlate and the regression should be able to provide a mathematical formulation of their dependency. This dependency could suggest that one entity causes the other, that both are caused by a hidden entity, or that they are involved in a complex system of relationships. The problem is to infer the causation from the relationship of the variables as correlation does not imply causation but indicates a possible causal relationship. In particular, correlation does not indicate the direction of causation.

Instead, correlation is a kind of degree of dependency. Usually it is assumed that the relationship between two variables is blurred

by noise (see also ANALYSIS OF VARIANCE AND COVARIANCE). The mathematical formulation of the relationship must consider these effects, which become particularly important when values have to be estimated or predicted.

While August Bravais and Francis Galton provided some ideas, it was Karl Pearson who developed the statistical method of correlation analysis (Nakoinz and Knitter 2016, 87–105; Rodgers and Nicewander 1988; VanPool and Leonard 2011, 221–237). His correlation coefficient, also known as Pearson's product-moment correlation coefficient, is a frequently used measure of the correlation of two variables. This correlation coefficient is the covariance of the two variables divided by the product of their standard deviations. The values range between -1 and 1 , and zero indicates no correlation. The measure is valid for interval scaled numbers. While the Pearson's correlation coefficient (ρ) is defined for whole populations, the sample Pearson's correlation coefficient (r) is defined for samples:

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}}$$

Both correlation coefficients are used for metric variables. In the case of ordinal variables, Yule's odds ratio (Q) can be used and for nominal variables Pearson's contingency coefficient or Goodman's and Kruskal's λ and τ are worthy approaches.

Francis Galton, who put the method of regression (Fahrmeir et al. 2013; VanPool and Leonard 2011, 178–220) into a statistical context, coined the term “regression.” The idea is that while mathematics traditionally starts with a formula and calculates values, regression works the other way around and reconstructs the formula based on a set of values.

The development of methods of regression originated with the problem of data fitting in astronomy. Adrien-Marie Legendre and Carl Friedrich Gauss developed the least squares method for fitting a function to a set of empirically observed values. Since then, many variants

of regression for different specific purposes have been developed.

The general idea is that the value of the dependent variable (also known as response variable, regressand, explained variable, predicted variable, or output variable, and symbolized with y) depends on the independent variable (also known as explanatory variable, predictor variable, regressor, controlled variable, or input variable, and symbolized with x) and a certain error (ϵ):

$$y = f(x) + \epsilon$$

A regression analysis has at least two steps: the determination of a regression model and the estimation of the regression coefficients. The first step deals with the regression model which is the type of function of the independent variable $f(x)$ in combination with some assumptions. Although it is possible to test the fit of multiple regression models, the decision which to use is usually based on theoretical considerations. The regression model needs to agree with both the theoretical knowledge of the phenomenon and the distribution of data.

The most simple regression model, which will be used as an example, is the simple linear regression model (see **LINEAR MODELS**):

$$f(x) = b_0 + b_1 x,$$

where b_0 is the intercept and b_1 the regression coefficient. In the case of multiple regression, an additional term of the type $b_i x_i$ is added for each covariable. The different covariables allow the expressing of different functions of the same variable. For instance, a polynomial regression model with $x_1 = x^1$, $x_2 = x^2$, and so on can be expressed by a multiple linear regression model. Such transformations allow the researcher a circumvention of the restrictions of a straight line as regression curve and offer a high degree of flexibility. While the linear regression model is the most popular one because of its flexibility, other frequently used regression models are the generalized linear regression model, logit regression model, polynomial regression model, and generalized additive model. Regression models can offer all possible curves.

All regression models are based on certain assumptions. In the case of simple linear models, the assumptions are:

- A linear relationship of the parameters. This assumption is rather trivial for a simple linear regression model with just two parameters but is an important assumption for multiple regression using more than one independent covariable. Many nonlinear models can be transformed to meet this assumption.
- The error of the observations is not correlated.
- The error is homoscedastic, meaning that the error has the same variance for all values of the independent variable.

Multiple regression assumes, in addition, additivity of the errors of the different covariables.

The second step of the regression analysis is the estimation of the regression coefficients (regression parameters). The least squares method is a mathematical technique (see **MATHEMATICS**) which minimizes the sum of the squares of the residuals, the difference between values of the dependent variable derived from the function and from observation. The residuals are a kind of estimated error; thus, by minimizing the residuals, the explanatory power of the regression model is maximized for finding the minimum sum of squares and the partial derivatives of the sum of squares with respect to the regression coefficients is set to zero. An algebraic transformation for simple regression leads to:

$$b_1 = \frac{\sum (y_i - \text{mean}(y)) (x_i - \text{mean}(x))}{\sum (x_i - \text{mean}(x))^2}$$

$$b_0 = \text{mean}(y) - b_1 \text{mean}(x)$$

In the case of normally distributed errors, the maximum likelihood estimation can be applied—this is another frequently used parameter estimation method.

The regression parameters estimated with this method maximize the likelihood of the occurrence of the empirical sample data in a distribution set by certain parameters. Usually, numerical methods such as the Newton–Raphson method are required for calculating the maximum likelihood function.

As a third step of regression analysis, the analysis of residuals can be applied. The general idea is that the regression model offers an explanation of a certain part of the observed variation and that the resulting error in the model is randomly

distributed and cannot be explained. However, the regression analysis results in an estimated error and not in a real value of the error. It is possible that the regression model is not sufficient for explaining all observations. A first indication of additional factors is the presence of outliers. In some cases, specific circumstances can be responsible for the values of the dependent variable and hence produce outliers. These outliers might not be observable with basic statistics such as mean and standard deviation analysis if they are inside the usual range of values. A regression analysis can make the outliers visible because they show that the values of the dependent variable lie inside the range of the whole dataset but not within the range expected for certain values of the independent variable. Certain structures such as autocorrelation of the errors are a second indicator of the importance of additional factors. Autocorrelation refers to a correlation of the differences of values of the independent and differences of values of the dependent variable. In simple words, similar values of the independent variable produce similar values of the dependent variable.

Another common issue in regression analysis is overfitting. The problem of overfitting is best explained by the example of polynomial regression:

$$y = b_0 + b_1x + b_2x^2 + b_3x^3 + \dots$$

The higher the degree of the polynomial, the better the fit of the regression curve. It is possible to produce a perfect fit if the polynomial degree equals the number of observations. If there is an error in the observations, the perfect fit does not make any sense because the regression model would map not only the valid data but also the error. This effect is called overfitting. The optimal degree of the polynomial can be estimated with a multiple subsampling strategy (see *SAMPLING THEORY*). In this method, one part of the observations is used to produce the regression curve and the other part is used to test the regression curve with the least square estimate or the maximum likelihood estimate.

In general, regression and correlation analyses offer a reasonable toolbox for investigating all kinds of relationships of variables. If time is used as the independent variable, the regression results in a model of the development of a certain phenomenon over time. But other variables such

as social indicators can also be investigated. For example, the correlation of the quantity of finds and the size of a burial monument can establish an indicator of social ranks and regression analysis allows the specification of the details of a relationship between the variables. The correlation of size and decoration of ceramic vessels can establish that the size is meaningful.

Fall-off curves are another well-known example of archaeologically useful regression models as they map the frequency of finds over the distance from a source. Mathematical distance decay functions are then used in order to deduce the organization of the exchange system.

Overall, regression models play a central role in landscape and environmental archaeology. Insights into the representativity of archaeological data can be gained by a correlation analysis of vegetation and the density of sites, while the correlation analysis of proxies for social change and environmental change tell something about the interrelationship of humans and the environment. A regression analysis of both sea level and age of sites is a specific type of a transgression curve and enhances the knowledge on archaeological sites and coastlines at different times. Regression analysis is the main tool of predictive modeling (see *PREDICTIVE MODELING*) where correlations between landscape features (e.g., altitude) and the degree of human activity are used to predict unknown sites.

Finally, regression methods are the main technique for predicting unobserved points. Inter- and extrapolation techniques are usually based on regression analysis. Interpolations (Nakoinz and Knitter 2016, 97–104) are carried out for reconstructing surfaces from samples such as coring or point measurements. If the regression does not use an explicit mathematical function, nonparametric methods such as kernel density estimation or kriging are applied.

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Sampling Theory

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There is a single objective underlying sampling theory: to create a subset of a population in which all cases in the subset have an equal probability of being selected from the population. A sample produced in this way will accurately reflect the range of variation in the population. All probabilistic methods of sampling are designed to achieve this basic objective. Four sampling methods based in probability theory are commonly used in archaeology: simple random sampling, systematic random sampling, stratified sampling, and cluster sampling. These methods all produce samples that match the statistical parameters of the population, and thus meet the requirements for statistical analysis. Several non-probabilistic methods are also commonly used in archaeology, but are not recommended to produce samples intended for analysis beyond basic descriptive statistics (and even these may be misleading).

Probabilistic sampling is based on the assumption that all natural populations have a “normal” distribution of variation from which the proportion of individuals with a given characteristic can be estimated. This assumption is visually demonstrated through the “normal curve” (see, e.g., Thomas 1986, Figure 7.12). A “normal curve” is a form of a histogram, where the range of variation for a given characteristic is shown on the *x*-axis and the number of individuals with that characteristic is shown on the *y*-axis. In a “normal curve” the arithmetic mean (the sum of all individual scores on the given characteristic divided by the number of individuals in the population) is the high point of the curve. The population variance is calculated as the sum of the squared differences between the value of each individual on the given characteristic and the mean, divided by the number of individuals in the population—in essence it is a measure of the average difference between an individual score

and the population mean. In practice the square root of the variance, called the standard deviation, is used to describe the population variance, as it is an arithmetically more useful measure.

Knowing the mean and variance (and standard deviation) of a population with a “normal curve” allows us to estimate the number of individuals in the population with a particular value on a given characteristic. For example, if the population has a mean of 100, a standard deviation of 10, and contains 1000 individuals, we can estimate that there should be about 20 individuals with a value of 110. An accurate sample of 100 individuals from this population should therefore contain 2 individuals with a score of 110. A good sample should contain cases that accurately match the proportion of cases with the same score in the population. Achieving that is the foundation of all probabilistic sampling methods.

Simple random sampling is the purest form of probabilistic sampling. To produce a simple random sample, every case in the population of interest is given a number. Cases for the sample are then selected using a random number generator, so that every case is selected randomly and thus each has an equal probability of selection. A sample produced by simple random sampling will have the same mean and variance as the parent population. Typically, only 10% of cases in the parent population need to be selected in order for a sample to accurately match its mean and variation.

Another method of random sampling is called *systematic random sampling*, and is often easier to perform in practice than simple random sampling. In systematic random sampling every case in the population of interest is assigned a number, just as in simple random sampling. But rather than selecting cases for the sample using a random number generator, in systematic random sampling only two random numbers are used—a random start and a random interval. The case with the random start is the first case selected for the sample, and then every case falling at the random interval following the start case is

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selected. For example, given a population of 1000, a researcher might simply use a dice to select a start case, say case number 2, and then a dice for the random interval, say 4. The researcher would select cases 2, 6, 10, 14, 18, 22, and so on for the sample. A sample produced in this manner will, like one produced by simple random sampling, match the mean and variation of the parent population. However, there is a caveat: systematic random sampling should not be used if there is a known or suspected periodicity in the population of interest, as the random start and interval might, by chance, match that periodicity, and thus all cases of a certain kind might be either systematically selected or systematically missed (Orton 2000, 22).

There is a significant problem in doing random sampling in practice, whether simple or systematic—the full range of the parent population is usually not known. Taking a simple example, we might want to do a study of the ceramics from an archaeological site. To create a simple random sample of that population we would first have to identify all the ceramics, which is pragmatically impossible. We know we could not have collected every ceramic unless we excavated the entire site, and even in that case we would have difficulty defining the boundaries of the site itself. And because ceramics are usually fragmentary, we would also have to decide how much of a given ceramic object we need to consider it part of the ceramic population. Because of problems like these, it is impossible to identify a “true” parent population in all but the most unique situations, and we must define them using specific criteria and focusing on a specific point in time and space. Thus, any population used in research is only an approximation of the “true” parent population, and any sample is an approximation of that approximation. This is a problem that no sampling method can overcome and we should remain mindful of it in making generalizations about any population we are studying (Thomas 1986, 439–47).

A second problem with random sampling is that we may be most interested in particular segments of a given parent population, and if these segments are relatively rare in the parent population, they will be equally rare in the sample. To acquire sufficient rare cases to perform

analyses might require a very large, and perhaps quite costly and time-consuming, sample to be taken from the parent population. In addition, if our parent population is spatially dispersed, collecting data on the cases selected through random sampling might be extremely costly and time-consuming, as the sampled cases might be separated by great distances. In both cases a more focused sample, either including more of the cases of interest or identifying cases that are spatially close, might be desired. These can be achieved using stratified or clustered random sampling.

In *stratified random sampling* we select separate random samples from several different groups within the parent population; for example, a random sample of those cases in which we are most interested and a random sample from the rest of the population. Knowing the mean and variance of the individual samples allows us to estimate the mean and variation of the parent population as well. And if our research requires us to compare the cases of interest with the rest of the population, this method of sampling provides a way to identify an adequate number of the rare cases to make those comparisons.

In *cluster sampling* we select simple random samples from defined spatial areas within the parent population. We might, for example, randomly select individual areas within a site and collect data from all cases in those areas. This might make the data collection much less costly and time-consuming than having to go all over the site to collect data from cases selected through simple or systematic random sampling. As with stratified random sampling, we can estimate the mean and variance of the parent population through those of the samples. We can also readily compare various areas within a site or region, if that addresses a question of interest.

Probabilistic samples are technically the only ones that should be used in statistical analyses, but pragmatically this is extremely difficult to achieve in archaeology, primarily because we typically know very little about our parent populations. With this in mind there are also several non-probabilistic sampling methods that are reasonable to use in situations where the parent population is completely unknown or where probabilistic sampling is impossible. These methods do not typically provide samples that match

the mean and variance of the parent population, and thus they cannot be used to make generalizations about the parent population (Kalton 1983, 90).

Opportunistic sampling selects all available individuals with a given characteristic for inclusion in the sample. For example, an archaeologist might analyze all the ceramics available in a local museum collection. *Grab bag sampling* is similar, but the archaeologist would select a group of those ceramics by non-systematic choice; for example, the first 20 ceramic objects s/he found in the museum collection. Grab bag sampling, although it may appear to use a random method, does not, because the probability of selecting a given case changes as items are chosen for the sample. Although often easier than probability sampling, non-probability sampling should only be used when probability sampling is impossible.

Regardless of the sampling technique used, it is important to determine an appropriate sample size. Sample size should balance the cost of collecting data and the accuracy required to evaluate a given hypothesis. By convention, a 10% random sample is considered adequate for most research problems. However, questions where very small differences (or *effect sizes*) between individuals or populations need to be evaluated require a larger sample, and where there are large expected differences, a large sample may actually provide too much accuracy, always finding differences even when they are not actually there (a *Type I error*). Determining sample size is often done

through *power analysis*. There are a number of power calculators on the Internet that provide a quick way to determine the appropriate sample size for a given hypothesis. It is important to note, however, that power analysis is only useful for random samples—another reason why random sampling should always be used whenever possible.

SEE ALSO: Descriptive Statistics; Human Populations; Hypothesis Testing; Inferential Statistics

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Seriation

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Seriation is a method for relative dating. The purpose of seriation is to arrange archaeological entities into a relative chronological sequence based on their formal properties. Archaeological entities can be analytical units at various scales, such as attributes of artifacts, artifacts, or assemblages of artifacts. Sir Flinders Petrie is credited as the founder of the method, although similar ideas were considered by his contemporaries, mainly John Evans and Pitt Rivers (O'Brien and Lyman 1999). The general principle of seriation is that archaeological entities or units should be rearranged in such a manner as to minimize the dissimilarity between adjacent pairs of entities in the sequence, for example, that the most similar entities are next to each other in the resulting sequence. The underlying logic is that the units that are most similar to each other in their formal properties (e.g., presence or frequency distribution of types in assemblages) are most likely to be close in time (Dunnell 1970). The temporal direction of the sequence (which end of the sequence is the earliest/latest) cannot be determined by seriation alone and must be established independently. O'Brien and Lyman (1999) defined three kinds of seriation:

1. *Phyletic seriation*: This is usually applied to attributes and artifacts, based on qualitative or metric variables. Attributes and objects are seriated based on their similarity (Figure 1a). In most applications, the phyletic seriation is based on the overall subjective judgment of similarity, but it can be made more formal by quantifying the features of analytical units, for example, by recording metric data.
2. *Occurrence seriation*: This is based on presences or absences of elements defining the units. The main principle behind the method is the *concentration principle* (Kendall 1963).

The concentration principle states that archaeological units should be arranged in such a way that the spans of elements (e.g., the span of presence of each attribute, or the span of each type) should be the shortest possible across the seriation sequence. Types can be seriated based on the presences/absences of attributes, and assemblages can be seriated based on the presences/absences of types (Figure 1b).

3. *Frequency seriation*: This was discovered by Alfred Kroeber in the early twentieth century. It is the most sophisticated kind of seriation, as it is performed on frequency data that contain extra information in addition to presence/absence data in occurrence seriations (frequency data can always be reduced to presence/absence data but not vice versa). It is usually applied on assemblages characterized by frequencies of types. The aim of frequency seriation is to order the units in such fashion that the relative frequencies of attributes/types follow a unimodal curve across the seriation sequence, which means that the relative frequency of each attribute/type should display monotonic increase, followed by decrease in relative frequency, after reaching a peak in relative frequency. It is also allowed for attributes/types to have truncated sequences in the sense that the relative frequency of an attribute/type may only increase or decrease across the sequence (Dunnell 1970). If this can be done, the resulting sequence is interpreted as a relative chronological sequence (Figure 1c). Therefore, in addition to the concentration principle, frequency seriation includes the *unimodality principle* or *popularity principle* which is based on empirical generalization that things slowly come into fashion, reach a peak of popularity, and slowly go out of fashion (e.g., different hair styles, clothes designs, architectural styles). It was noted in cases where relative chronology is known independently that frequencies of certain attributes/types of a certain class of material culture indeed change according

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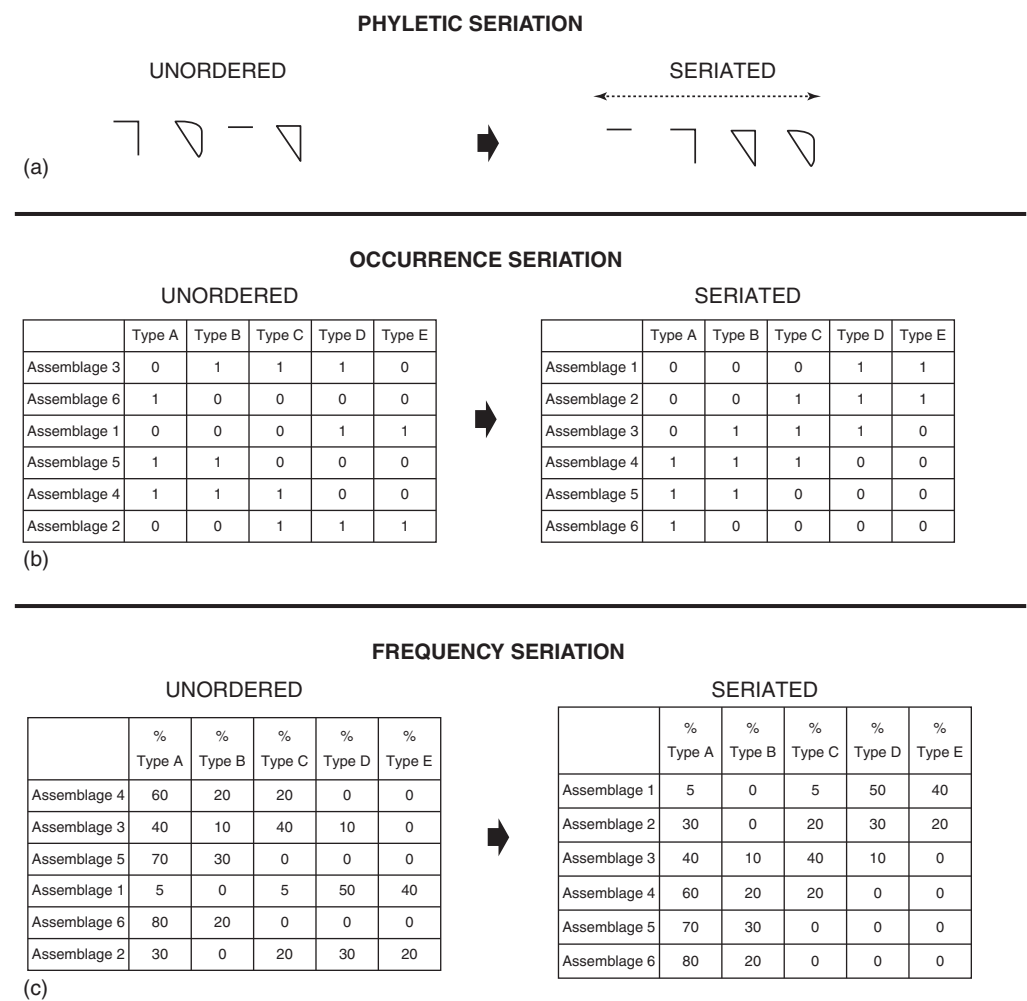


Figure 1 Late Neolithic Vinča culture clay figurine eye shapes. (a) Phyletic seriation. (b) Occurrence seriation (hypothetical data). (c) Frequency seriation (hypothetical data).

to or approximating the popularity principle. Three preconditions must be met for seriation to be applicable (Dunnell 1970):

- All units must be of comparable duration. For example, if this precondition is not met, the occurrences or frequencies of attributes/types in different assemblages will also be affected by the duration of assemblage formation rather than by temporal change alone.
- All units must come from the same cultural tradition. This precondition ensures the *heritable continuity* (O'Brien and

Lyman 1999)—the cultural relatedness of units through time.

- All units must come from the same spatial area. This precondition prevents the conflation of temporal and spatial effects on archaeological units—for example, if cultural interaction is dependent on spatial distance, variation in typological composition of assemblages may arise between contemporary assemblages resembling variation due to temporal effects.

There are many techniques of seriation in archaeology. James Ford developed the famous

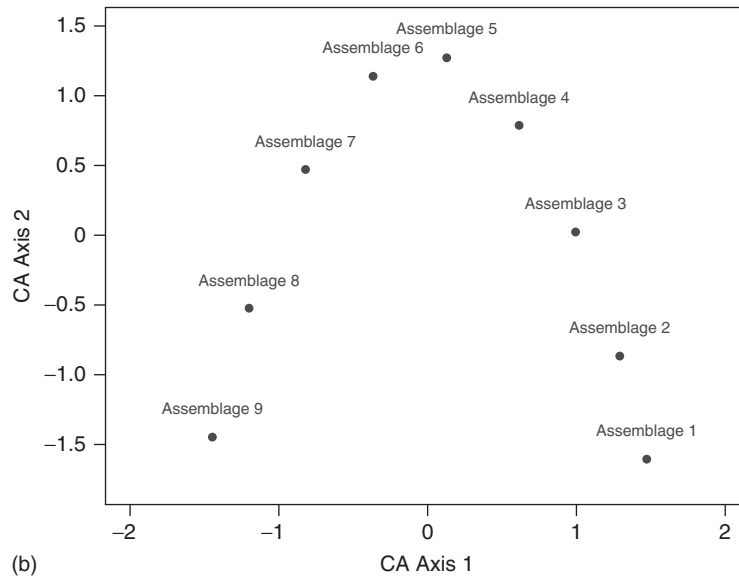
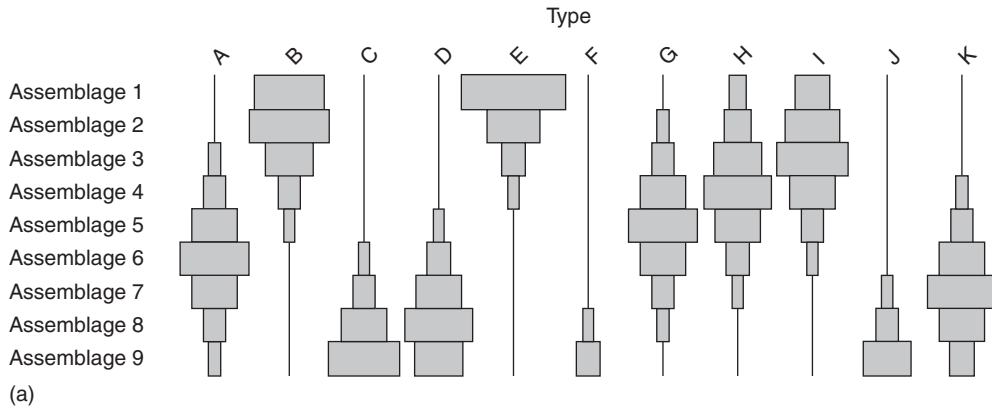


Figure 2 (a) “Battleship” seriation diagram. (b) Correspondence analysis (CA) plot (based on dataset from panel a).

hand-sorting technique for the frequency seriation (O’Brien and Lyman 1999). The first step was to graphically represent the percentages of types in each assemblage on individual narrow paper strips. The percentage of each type in each assemblage was represented by the width of a horizontal bar. The analyst would rearrange the paper strips until the sequence was such that the relative frequencies of all or at least most of the types behaved in accord with the unimodality principle. The visual patterns resulting from valid seriations constructed by Ford’s method were named “battleship curves,” as they resembled a silhouette of a battleship from a bird’s eye view (Figure 2a).

Brainerd (1951) and Robinson (1951) developed a seriation technique based on a specific quantitative similarity coefficient—the *Brainerd–Robinson (BR) similarity index*. The first step in this technique was to calculate the BR similarity index between all pairs of assemblages. The value of the similarity between assemblages i and j is equal to the sum of differences of percentages between assemblages i and j for all n individual types, subtracted from 200:

$$BR_{ij} = 200 - \sum_{k=1}^n |P_{ik} - P_{jk}|$$

The greater the value of the BR index for a pair of assemblages, the more similar they are. When BR values are calculated for all pairs of assemblages, they are arranged into a quadratic symmetric matrix. In order to obtain the valid seriation sequence, an analyst should rearrange the sequence of rows (and columns) until the matrix takes such form that the values of the BR coefficient are decreasing as one moves away from the main diagonal of the matrix.

With real-world data it is often the case that there is more than one sequence that satisfies the conditions of the seriation (e.g., more than one way to arrange the assemblages to obtain or approximate the unimodal model or to minimize distances between assemblages in a sequence). In theory, one could “try out” every possible sequence and see which, if any, fits the seriation model best. In practice, the number of possible permutations increases rapidly. Even with the aid of the fastest computers, it is not possible to look at each possible permutation, even for a relatively small number of units (Lipo, Madsen, and Dunnell 2015).

For this reason, most seriations in modern archaeology are performed by conceptualizing seriation as a multivariate problem of ordering and then applying an appropriate multivariate technique. Each unit is described by the presence/absence or frequency data in a multidimensional space defined by attributes/types, where each attribute/type represents a dimension, and the particular configuration of presences/absences or frequencies in a particular assemblage defines the position of that assemblage in a multidimensional space. The aim of applying multivariate techniques is to find a single dimension, which accounts for the greatest proportion of variability in the data, and to rank units along that dimension. This dimension is interpreted as time, because it is assumed that temporal effects are the main cause of variability between units (which should be the case if the third precondition of seriation is met). The two most commonly used multivariate techniques are multidimensional scaling (MDS) and correspondence analysis (CA) (see CORRESPONDENCE ANALYSIS). MDS is applied to a matrix of pairwise similarities or distances between objects or assemblages, whereas CA is applied directly to the occurrence of frequency data matrix. The results

of MDS- or CA-based seriations are presented graphically on a 2D scatter-plot (Figure 2b). The first dimension, which accounts for the greatest proportion of variability and is interpreted as time, is presented on the *x* axis. An important criterion for a chronological interpretation of both MDS and CA results is the presence of an arch effect (the tendency of units to form an arch on a 2D scatter-plot). The arch effect is an indicator of unimodality, as it is a mathematical consequence of projecting the multidimensional unimodal gradient in 2D space. In most cases, seriation is performed on samples rather than populations, implying that the resulting solutions are always affected by sampling error; therefore, additional tests are necessary to take this into account (see Lipo et al. 1997).

Cultural transmission theory provided an explanation of why seriation works as a reliable method in archaeology. It was shown by computer simulation that one of the fundamental models in cultural transmission theory, the unbiased transmission (the neutral evolution model), produces approximately unimodal relative frequency patterns (Neiman 1995). It was also shown that space can affect seriation in a predictable manner, which makes it possible to define areas of cultural interaction by using seriation as a criterion for grouping sites—a group of site assemblages conforming to the seriation model can be interpreted as representing one cultural interaction sphere (Lipo et al. 1997).

Significant improvements were made within the cultural transmission theory framework both in the theoretical understanding of the processes that generate seriation patterns and in the development of the method itself. A recently introduced iterative deterministic seriation solution (IDSS) method simultaneously solves several problems (Lipo et al. 2015). It finds the best seriation solution in absolute terms and ensures the goodness of fit by statistically comparing the frequencies of types between assemblages in a sequence, controlling for the sampling error at the same time. It allows for branching seriation solutions—the possibility that units do not fall on a single sequence but may belong to diverging sequences. If once a single regional interaction sphere splits into two spheres (e.g., interaction between two subregions stops), a single seriation sequence with units from both subregions will

at some point branch into two sequences, each made of units from different subregions. The classic seriation method, especially when performed with multivariate techniques, cannot retrieve this pattern. These latest developments demonstrate that the epistemic potential of seriation goes beyond relative dating—it can be used to solve interesting questions of cultural dynamics in both space and time.

SEE ALSO: Dating in Archaeology;
Multivariate Analysis

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Statistics and GIS

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Statistics contribute strongly to GIS analysis activities including: data exploration, classification, and visualization; spatial analysis; interpolation and modeling; and error calculation and assessment. Exploring, classifying, and visualizing geospatial datasets are essential precursors to GIS analysis relying heavily on descriptive statistics. Inferential statistics enable spatial analysis of point and areal patterns. Remote study areas and/or physical variable collection (e.g., precipitation, elevation, etc.) require statistical surfaces to interpolate (estimate) unmeasured locations. Statistical models explain or predict spatial variable values and patterns. Statistics also inform error calculation and assessment for spatial modeling, interpolation, data digitization, GNSS data collection, and remotely sensed data correction.

Data exploration, classification, and visualization

Aspatial central tendency metrics such as mean, median, and mode, and aspatial dispersion metrics such as variance, standard deviation (SD), and coefficient of variation (CV), are the most common statistics. The CV normalizes the standard deviation by the mean, permitting direct variation comparisons between different datasets and variables. Not conducive to mapping, skew and kurtosis impact GIS analysis because their characteristics affect assumptions and inferential techniques applicable to a dataset. For example, many inferential statistical procedures and linear regression models require normal distributions.

Spatial central tendency metrics include central features, mean centers, and linear directional means (LDMs). Central features have the smallest Euclidean distance to all locations in a dataset,

and may represent point or areal data. Central feature identification plays an important role in locational analysis, facility siting, and service provision (e.g., emergency services, public transportation, etc.). Mean centers represent the average location for a georeferenced point set by separately averaging x and y coordinates. The most common mean center application is the geographical *center of population* calculated every decennial census by the US Census Bureau (McGrew et al. 2014). Weighted mean centers are mean center variants, where x and y coordinates are weighted by an attribute value frequency (e.g., sales volume, rainfall, etc.). LDMs are average directions calculated from the mean angle of a set of linear features. Common LDM applications include analysis of transportation systems, migration patterns, and flight paths, to determine average orientation or directional changes over time. Like aspatial measures, spatial central tendency metrics are strongly influenced by outliers, and require careful interpretation.

Spatial dispersion metrics include standard distance and relative distance. Spatially equivalent to the standard deviation, standard distance measures absolute point dispersion relative to the mean center. Weighted standard distances follow a similar rationale as weighted mean centers, and are appropriate when weighted mean centers best describe average location. Functionally similar to standard distances, standard deviational ellipses additionally consider point pattern orientation, using two axes where x and y coordinate distance variations are considered separately. Spatially analogous to the CV, relative distance divides the standard distance by the radius of a circle with the same area as the study region, and helps researchers make equivalent dispersion comparisons between different size study areas and disparate datasets.

Understanding data classification basics is important because classification schemes and numbers of classes selected influence interpretations of inherent spatial patterns. Equal interval (EI), quantile breaks (QB), natural breaks (NB), and standard deviation breaks (SDB) are the

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most common classification schemes available in most GIS packages. EI classifications use equal class widths with variable numbers of features in each class. Range EI methods partition differences between maximum and minimum values into desired numbers of classes, occasionally producing misleading results. Non-range EI methods improve pattern interpretation using arbitrary analyst-defined breaks, but may mask internal variation. QBs divide all features equally into predetermined numbers of classes, reducing sampling bias. Quartiles and quintiles are the most common quantile classifications due to the ease of overall pattern interpretation, but individual classes may not be intuitive.

Natural breaks (NB) partition data using *natural* gaps (breaks) in the frequency distribution, to create unequally sized groups of similar and dissimilar values. NB methods highlight extremes in spatial datasets, maximizing and minimizing between-class and within-class variation respectively. “Jenks natural breaks” is the most common technique, and is the default classification in many GIS packages. SDBs use predetermined numbers of standard deviations above and below the mean to separate data into classes, and works best with normally distributed data.

Spatial analysis

Point pattern analysis determines dataset point arrangements to identify spatial process presence or absence, and includes nearest-neighbor analysis (NNA) and quadrat analysis (QA). For point sets, NNA compares the mean nearest-neighbor (Euclidean) distance (NND) to theoretical distributions of random, clustered, and dispersed points. NNA test statistic values greater than, less than, and equal to the random pattern's mean NND suggest clustering, dispersion, and randomness, respectively.

QA uses point frequency within areal tessellations (zones) to determine relative dataset clustering, dispersion, or randomness. Variance mean ratio (VMR) values equal to one, greater than one, and less than one respectively suggest randomness, dispersion, or clustering. The testable QA statistic is a chi-square distribution

generated from the product of the VMR and one less than the total number of quadrats.

Areal pattern analysis determines dataset zonal arrangement, identifying spatial process presence or absence using Moran's I, Local Moran's I, and Getis-Ord G_i^* indices among others. Moran's I provides quantitative global spatial autocorrelation measures using a given attribute's (e.g., precipitation) zone centroid arrangement, and adjacency or Euclidean distance-based spatial weights matrices. Positive Moran's I values suggest that attribute values are more clustered than a random distribution, and negative values suggest more dispersion. Monte Carlo simulation is applied to Moran's I calculations, generating a testable statistic with pseudo p -values (O'Sullivan and Unwin 2010).

Local Moran's I is a local version of global Moran's I, where degrees of spatial autocorrelation are calculated for each study area zone's attribute value (Anselin 1995). Positive Local Moran's I values indicate similar attribute value clustering, and negative values indicate dissimilar values located near each other (dispersion). Mapped with GIS and combined with Moran scatterplots (Anselin 1995), Local Moran's I values and z -scores differentiate between high and low value clusters, and identify influential zones contributing most strongly to corresponding global spatial autocorrelation measures. Getis-Ord G_i^* also identifies clusters of high (hot spots) and low (cold spots) attribute values within a study area (Getis and Ord 1992), using Euclidean distance-based spatial weights matrices.

The “modifiable areal unit problem” (MAUP) and distance criterion selection influences all spatial statistics, because changing distance thresholds yields different resulting pattern interpretations. Multi-distance tools such as Ripley's K help ameliorate this problem. Available in most GIS packages, Ripley's K calculates degrees of clustering or dispersion in a point set at multiple distance intervals. More specifically, Ripley's K $L(d)$ function identifies minimum distances where statistically significant clustering is maximized, as well as distances where point or zone arrangement is unlikely to influence nearby attribute values.

Spatial interpolation and modeling

Statistical surfaces are generated using exact or inexact interpolators. Exact interpolators estimate values at unmeasured locations using measured values, while measured values represent themselves. Conversely, inexact interpolators use measured values to estimate measured and unmeasured values (Chang 2016). Inverse distance weighting (IDW) and Kriging are common exact interpolators, while trend surfaces (TSs), regression, and kernel density estimators (KDEs) are typical inexact interpolators. Inexact interpolators offer benefits such as error calculation and confidence interval estimation.

IDW interpolators use distance decay and a Euclidean distance threshold. Distance decay functions determine nearby point influences within the distance threshold, where higher-order functions increase the influence of points closer to the estimated point, and vice versa. Default IDW implementations use second-order functions, and increasing function order produces smoother surfaces. IDW interpolations are sensitive to distance threshold selection due to the MAUP.

Kriging partitions geospatial datasets into spatial trends, or spatially correlated components based on a cardinal direction, spatial correlations between attribute values at nearby locations, and random error terms, to select optimal spatial weights for unmeasured point interpolation (Chang 2016). Basing optimal weight selection on measured values reduces MAUP influences affecting other interpolators and spatial statistics. Kriged surfaces remove spatial trends (drift), and estimate unknown values using residuals. Kriging is the preferred lidar digital elevation model generation method.

TSs fit polynomial equations to known values, estimating values at all study area locations, and produce highly generalized global spatial patterns that reduce noise introduced by local interpolators. Complex surfaces such as topographic variation (e.g., hills and valleys) require third-order polynomials or higher. Also a global interpolation method, regression estimates values for measured and unmeasured locations using measured values. Regression predicts (estimates) dependent variable values using one or more independent variable values. Additionally,

errors between known and estimated values are calculable for regression models.

KDE interpolators estimate unmeasured values by applying probability density functions (PDFs) to points falling within the kernel's bandwidth (distance threshold). Conceptually, KDEs form a *bump* centered on the estimated point, and all measured value influences within the bandwidth are weighted according to the PDF. Like IDW interpolators, KDE methods are sensitive to the distance threshold selected. This sensitivity is addressed using a fixed or adaptive kernel bandwidth. Ripley's K helps analysts to determine an appropriate fixed bandwidth, while adaptive bandwidths self-adjust kernel bandwidths for each individual point estimated.

Using ordinary least squares (OLS), global linear regression estimates dependent variables from one or more independent variables. OLS models assume normally distributed data, and no spatial structure. Although OLS models are inherently aspatial, they remain insightful spatial analysis tools. For example, searching for evidence of clustering, Connolly and Hagelman (2015) mapped residuals from several multivariate OLS municipal water consumption driver models. OLS residual clustering often suggests spatial process presence, which may be verified using spatial statistics such as Moran's I and Local Moran's I.

Local regression assumes a spatial structure in the dataset, and develops individual models for each point or region. Rather than OLS, local regressions use modified weighted regression, where regression weights are distance thresholds (spatial weights). Geographically weighted regression (GWR) applies PDF kernels with fixed or adaptive bandwidths to each independent variable in the model to estimate the value at the kernel center. Despite its ability to capture spatially varying relationships, GWR's frequent use of varying kernel sizes (i.e., adaptive kernels) can produce multicollinearity problems which inflate overall model fits. Simpler bivariate and multivariate spatial regressions also exist, but are considered semi-local models because uniformity in each independent variable's spatial variation is assumed across the study area (O'Sullivan and Unwin 2010).

Error calculation and assessment

Error assessments are commonly applied to modeling and interpolation results, geometric transformations (e.g., satellite and aerial imagery orthorectification, and paper map georeferencing), and global navigation satellite system (GNSS) data accuracy. Modeling and interpolation results are assessed using validation and cross-validation methods. Validation methods partition data into two groups. The first group is used to develop the model or interpolation, and the second group is used to calculate the difference (error) between the two groups. Cross-validation methods (leave-one-out validation) omit a single observation and use remaining observations to estimate omitted values, and calculate associated errors. This process is repeated for every original dataset observation. Preferred diagnostic statistics for these error assessments are root mean square error (RMSE) and standardized RMSE.

RMSE is also commonly applied to determine errors in satellite and aerial imagery geometric transformations, analogue spatial data digitization (e.g., paper maps), and remotely sensed data co-registration for change detection analysis. These operations all require carefully selected ground control points (GCPs) with precisely known locations. RMSE calculates the error between transformation or correction results, and the GCPs.

GCPs are often collected via roving GNSS receivers, and require their own positional error assessment. GNSS data positional errors result from internal satellite clock, signal transmission and receipt, and satellite geometry problems. Satellite geometry problems are estimated using dilutions of precision (DOPs) measured for horizontal, vertical, and overall position (PDOP) characteristics, with PDOP being most common. PDOP is the ratio of the four most widespread satellites available at a given location, to an idealized areal coverage. PDOP and other positional errors may be partially removed via post-processing techniques, such as differential

correction. Sufficiently large samples can yield a 95% confidence level within two standard deviations of the actual location recorded with the roving GNSS receiver.

SEE ALSO: Descriptive Statistics; Digital Cartography; Digital Photogrammetry; GPS (Global Positioning System); Imaging; Inferential Statistics; Linear Models; Regression and Correlation Analysis; Sampling Theory; Spatial Analysis

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Statistics in Archaeology

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Statistical analysis in archaeology depends on the archaeological record as the main source of observations (see *ARCHAEOLOGICAL RECORD*). The archaeological record consists of objects and features that must be collected, recorded, measured, and organized. The recovery and recording of the archaeological record must be informed by the research questions that will be addressed using its data. Inherent in its definition, statistics may be used to examine groups of empirical observations for the purposes of description, inference, and discovery. Observations on objects include provenience, age, composition, measurements recording size and shape, and measurements recording surface characteristics. Features are bounded spaces that often contain objects. Observations on features include provenance, age, measurements recording size and shape, internal stratigraphy, and counts of different kinds of objects and features. Since archaeological sites are rarely excavated in their entirety, it is important that the objects and features recovered represent the unexcavated parts of the site or of similar sites that have not been excavated. Sampling statistics provide a way of ensuring that the data recovered are representative of the population, and provide estimates of the sample sizes needed to answer the research questions (see *SAMPLING THEORY*).

Statistical analysis of archaeological data generally falls into one of five broad domains: composition (see *COMPOSITIONAL DATA ANALYSIS*), chronology (see *RADIOCARBON CALIBRATION AND AGE ESTIMATION* and *SERIATION*), classification (see *ARCHAEOLOGICAL CLASSIFICATION*), spatial distribution, and quanta (see *QUANTUM ANALYSIS*). All have their origins in the nineteenth century, but the increasing availability of computing equipment after World War II facilitated steady growth in their use. Papers by

Robinson (1951) and Spaulding (1953) addressed chronology (seriation) and classification (association between nominal variables). Since 1958, the journal *Archaeometry* has published object composition studies regularly. The study of assemblage variability may be linked to Binford and Binford's (1966) use of statistical methods to determine whether the variability in tool types within Mousterian sites could be explained by something other than Bordes' suggestion that it represented different cultural groups. In 1968, the publication of *Analytical Archaeology* by David L. Clarke made a strong case for quantitative methods in the field. In the early 1970s, spatial distribution analysis and methods from ecology and geography diffused into archaeology with the publication of Whallon's (1973, 1974) research on space occupation, and the seminal contribution to spatial analysis in archaeology by Hodder and Orton (1976).

Composition studies can be divided into object composition and assemblage composition. Object composition involves careful control over sample size and presentation of results as ratios (parts per million, billion, etc.). Assemblage composition involves less control over sample size and presentation of the results, as counts of different kinds of objects (e.g., the number of each of 66 types of Mousterian tools in a particular stratum). Statistical methods for object composition draw primarily on traditional multivariate statistics (see *COMPOSITIONAL DATA ANALYSIS*). Statistical methods for assemblage composition draw primarily on the ecological literature relating to community composition and species diversity. Chronological studies include methods of seriation that have been developed since Petrie first posed the problem in 1899. Later, Robinson (1951) and Kendall (1963) developed formal criteria and methods for seriating assemblages. Chronometric dating has benefited from the development of Bayesian methods, making it possible to incorporate prior information that has strengthened the kinds of inferences that can be drawn from groups of radiocarbon ages (see *RADIOCARBON CALIBRATION AND AGE ESTIMATION*). Classification studies include methods

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to find or create groups of artifacts or features and to explore alternative explanations for those groups. For example, they may represent different chronological periods or differences in the activities performed at the site. Recent developments such as geometric morphometrics allow the analysis of three-dimensional coordinates to describe object shapes and to group them. Analysis of spatial distributions has advanced with the development of geographical information systems (GIS) for managing spatial data, and analytical methods to compare observed data with theoretical spatial distributions (see STATISTICS AND GIS).

Archaeological data measurement is the process of recording observations on objects and features (see MEASUREMENT THEORY). There are four different ways to record a measurement. Nominal or categorical measures assign a label or category. The categories do not have any inherent ordering, but they are mutually exclusive and should be exhaustive. For example, a pot might be painted, incised, or plain. Ordinal measurement assigns a rank value to an object or feature so that one object is larger or smaller, but we cannot say by how much. The third and fourth types of measurement are expressed numerically. Interval measures have an arbitrary zero point (such as temperature scales, calendar dates, and compass directions). Ratio measurements have an absolute zero so that a projectile point that is 5 cm is twice as large as a point that is 2.5 cm. Within ratio measurements, some measurements are discrete, meaning that only integer values are possible. There can be 1, 2, or 3 flakes, but not 2.5 flakes. Other measurements are continuous so that decimal values are possible.

The description and visualization of archaeological data is a first step in verifying the accuracy of the data, identifying outliers, and identifying the data distribution. Descriptive statistics include methods for describing the distribution. Plots provide more information about the distribution of values, including histograms, kernel density plots, cumulative plots, box-and-whiskers plots, and strip plots. One goal of the plots is to see whether the distribution of values resembles a known distribution such as a normal or log-normal distribution for continuous numeric values, or a Poisson distribution for count values. Another goal is to identify observations that seem

anomalous. Anomalous values or outliers may be present in the data as a result of coding or transcription errors, or they may also represent valid observations. In some cases, it would make sense to exclude outliers. Generally, it is preferable to use robust statistics that are not as greatly affected by outliers. Missing values should also be identified at this stage. Handling missing values can involve removing observations or variables with missing values, or imputing values using one of a number of approaches designed to avoid biasing the sample mean and standard deviation.

Descriptive statistics also involve the comparison of two or more variables to determine whether they are correlated or associated with one another. For numeric or ordinal variables, correlation coefficients summarize a tendency for one variable to increase or decrease when another variable increases or decreases (see REGRESSION AND CORRELATION ANALYSIS). For nominal variables, measures of association summarize a tendency for categories of one variable to be associated with categories of another variable (see CHI-SQUARE ANALYSIS).

Inferential statistics involve inferences about populations from samples. Since the data consist of only some of the objects, features, and patterns of association produced in the past, inferential statistics are necessary to draw conclusions that extend beyond the data at hand. If there are two samples it may be important to know whether they derive from the same population. If two variables seem to be related to one another, it may be important to know whether this relationship characterizes the population or is just an artifact of this particular sample. Answering these questions involves two different but related procedures: confidence intervals and hypothesis testing.

Both approaches assume that the observations are independent of one another. This becomes important in archaeology where objects are often fragmented. Fragments of the same object are not independent of one another: an important assumption of inferential statistics. As a result, archaeologists have developed various indices to estimate the number of whole objects represented by a collection of fragments (see LITHICS DATA QUANTIFICATION and POTTERY DATA QUANTIFICATION).

Inferential statistics also play a role in evaluating statistical models. Statistical models generally show the relationships between a response (dependent) variable and a group of explanatory (independent) variables. Analysis of variance (see ANALYSIS OF VARIANCE AND COVARIANCE) is used, primarily, in experimental contexts to determine whether various treatments (explanatory variables) result in difference outcomes (measured with a nominal response variable). When the response variable is numeric, regression analysis (see REGRESSION AND CORRELATION ANALYSIS) summarizes the degree to which variation in the response variable can be predicted by variation in the explanatory variables. Regression analyses include several related methods including multiple linear regression, nonlinear regression, robust regression, logistic regression, and Poisson regression (see LINEAR MODELS). In logistic regression, the response variable is a dichotomy, while in Poisson regression the response variable is a count.

Statistical learning (Hastie, Tibshirani, and Friedman 2009) and exploratory data analysis (Tukey 1977) are umbrella terms for collections of methods that emphasize identifying interesting patterning in the data and using data to construct predictive models. Statistical learning includes traditional multivariate statistical methods (see MULTIVARIATE ANALYSIS) as well as more recently developed approaches. Broadly there are two approaches: supervised and unsupervised (see SUPERVISED PATTERN RECOGNITION). In the supervised approach, we know what the response variable is. However, we want a way of characterizing it using a set of variables. For example, we have obsidian samples from known sources and we want to construct a way of identifying the source for samples from archaeological sites. Unsupervised approaches are more difficult since we have only explanatory variables, and the challenge is to infer the response variable. For example, we have pottery from many sites that we suspect was produced in a few locations and we would like to identify those compositional groups.

A basic problem in multivariate statistics is that it is difficult to visualize relationships between many variables or clusters of observations in multidimensional space. Plots of objects and features using two dimensions or three dimensions

(variables) are straightforward. When there are more than three variables, it is necessary to find a two- or three-dimensional view of the data that captures as much information as possible. For example, in a sample of projectile points, length, width, and thickness are usually correlated with one another since large points tend to be longer, wider and thicker. We could summarize size as a single variable and then construct additional variables that capture aspects of point shape. This is an unsupervised problem since all of the variables are explanatory. The created variables are called latent variables, because they are not directly observable. They are inferred from the correlations between the variables.

Principal components analysis (PCA) is the standard way to accomplish this (see PRINCIPAL COMPONENT ANALYSIS). PCA creates the same number of variables (called principal components) as the original data contain. The first variable contains the greatest amount of covariance between the variables, and the second variable contains the next greatest amount of correlation with the constraint that the correlation between them is zero, and so on. Often the first two or three principal components represent much of the variation in the larger set of original variables. The loadings for each principal component provide an indication of what variables are important on that component, and the scores provide an indication of which objects are similar on that component. The loadings and scores can be plotted separately or overlain on a biplot to examine the patterns in the data. A similar procedure, factor analysis, also extracts latent variables (called factors), but focuses on factors that are interpretable rather than just descriptive (see FACTOR ANALYSIS).

When the data consist of a collection of assemblages (see ASSEMBLAGE), the variables are counts representing the number of artifacts of different types, and correspondence analysis (CA) generally gives better results (see CORRESPONDENCE ANALYSIS). In a cross-tabulation of artifact types by locations, there will often be interactions between combinations of artifacts and locations that are difficult to recognize just by examining the table. One reason is because the artifacts and locations are presented in an arbitrary order, and another is that the sample sizes (i.e., the total number of artifacts in each assemblage) can vary

substantially. CA creates latent variables (called dimensions) for the rows and the columns. Plots of the dimensions can be examined separately or overlain in a biplot, as with PCA. The values on the first dimension can be used to reorder the rows and columns in the original table, and these orderings often provide a good seriation if there are temporal differences between the assemblages.

Another way of reducing the dimensions in a dataset is to compute a measure of distance (see *DISTANCE AND DATA TRANSFORMATION*) between all pairs of rows and to use multidimensional scaling (MDS) to create a reduced set of dimensions based on these distances. There are metric and non-metric versions of the procedure. It is often the case that PCA, CA, and MDS produce very similar configurations, but given the speed of modern computing equipment, it is useful to try all three.

The combination of objects or features into groups based on their similarity is another unsupervised approach. For example, a collection of artifacts might represent multiple stylistic or functional types, but we do not know what they are. In this case we are trying to identify clusters of objects in multidimensional space. Cluster analysis includes two broad approaches: partitioning methods and hierarchical methods (see *CLUSTER ANALYSIS*). Partitioning methods divide the objects into a fixed number of groups. They include K-means, K-medoids, and methods based on density or assumed underlying distributions. K-means divide the data into K groups where K is specified in advance. K-means can be very fast, but it is useful to run the procedure multiple times using different numbers of groups and different starting configurations. Density-based approaches look for areas of high density in multidimensional space to form clusters. Distribution-based methods require the specification of the distribution model (usually multivariate normal), which may not always be appropriate.

Hierarchical methods define cluster memberships for all possible group sizes from 1 (everything is in one group) to N , the number of observations. The results are depicted in a dendrogram showing the progressive reduction (or increase) in the number of groups as the analysis proceeds. Agglomerative methods work

from N to 1, while divisive methods work from 1 to N . Agglomerative clustering requires making four decisions. First, will the variables be equally weighted (e.g., computing standard scores) or not? Second, how will distance be measured? There are multiple distance measures and they can affect the results. Third, how will the distance from an object to a group of objects be measured (sometimes called the clustering method)? Again there are a number of choices. Trying multiple clustering methods is usually advisable. Finally, how many clusters are useful to work with? Divisive clustering is very hard to implement when there are many numeric variables and many observations, so simplifications are necessary. Divisive clustering with presence/absence variables is simpler. An example is the construction of phylogenetic trees.

Hierarchical methods do not require specifying the number of clusters in advance, since membership for all possible cluster sizes is depicted in the dendrogram. However, that just postpones the decision of how many clusters to use. The number of clusters present in the data is not a simple question. There are multiple methods of suggesting the best number of clusters and they often disagree. An equally difficult question is: how “real” are the clusters? To what degree have we just divided random data into homogeneous groups? It is probably more accurate to say that cluster analysis “makes” clusters than to say it “discovers” them. Generally we are creating groups for some purpose such as comparing the groups with external criteria. For example, do the groups show a tendency to be concentrated in certain stratigraphic levels, or certain areas of the site? Are some groups associated with particular features? Do the groups differ in use wear indicators?

Supervised analyses have the advantage that there is a response variable. The goal is to use the explanatory variables to predict the response variable for those cases when it is unknown. Compositional analysis involves samples of objects (stone, ceramics, metal) from known sources (geological or manufacturing) and variables describing their composition (see *COMPOSITIONAL DATA ANALYSIS*). The sources are used to construct predictive equations that can be used to predict the source when it is unknown in order to study ancient trade networks. The

most commonly used method in archaeology is linear discriminant analysis (LDA). Whereas PCA tries to summarize the correlations between groups of variables, LDA tries to construct latent variables that provide the best separation between the sources. The equations generate posterior probabilities that can be used to identify which source an unknown specimen matches most closely. To be reasonably confident that the object belongs to a known source, typicality probabilities are used to see whether the object is a good fit with that compositional group. Other supervised methods that archaeologists are beginning to explore include classification and regression trees, random forests, and support vector machines.

As the variety of statistical methods that can help to answer archaeological questions has increased, the availability of software to implement those procedures has also increased. Each method comes with assumptions and limitations. Methods that test specific hypotheses are still important, but newer methods provide richer ways of interacting with the data to stimulate development of new ideas about how to use the archaeological record to learn about the past.

SEE ALSO: Archaeological Classification; Bayesian Statistics; Descriptive Statistics; Exploratory Data Analysis (EDA); Inferential Statistics; Multivariate Analysis; Nonparametric Statistics; Sampling Theory; Supervised Pattern Recognition

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FURTHER READINGS

Supervised Pattern Recognition

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The term “pattern” refers to an example or model that can be copied. Moreover, it can be interpreted as an imitation of a model as well. Patterns can describe different types of objects that are contained within the physical and abstract worlds by means of their interrelation of data, events, concepts, and context. Therefore, they can be perceived even with a certain level of distortion, ambiguous or incomplete information, or the presence and affectation of noise. As an example, if the letter “P” is distorted, it could be a “P” or an “R,” or even a totally different letter. However, if the letter appears in the word “OARK,” then it has a higher possibility to be the letter “P,” but if it appears in the word “OOAD,” then it is more likely to be the letter “R;” this means that the main context used by the word in the experiment defines the correct letter even with its distortion, which explains the crucial importance of the context in a pattern recognition process (Shih 2010).

The pattern recognition process can be described with two main tasks. One of them is the development of a decision rule that will be based on human knowledge; this is known as the learning process. The rule that has been previously defined for the decision-making process and which will be applied to an unknown pattern is defined as the classification process. The learning process is concerned with the study of recognition mechanisms of patterns by human and other living organisms. The classification process deals with the development of the theory and technique needed for an automatic recognition task. The application of the pattern recognition theory can be grouped as:

- Human–machine interaction and communication: including automatic speech

recognition, optical character recognition (OCR) systems, knowledge extraction from natural language, speech understanding techniques, and image and video processing including artificial vision.

- Biomedical applications: including electrocardiogram (ECG) analysis, electroencephalograms (EEG) analysis, electromyography (EMG) analysis, X-ray analysis, image processing techniques, and audio and signal processing methodologies.
- Physics: including high-energy physics, astronomy, and quantum mechanics.
- Criminology studies: including analysis of fingerprints, handwriting, speech, sound, and photography as evidence.
- Natural resources management: including the main study of agriculture, hydrology, forestry, geology, environment, cloud formation, urban assessment, aerosols, and particles.
- Military applications: All the previous groups are included, adding detection of nuclear hazard, missile guidance and detection, radar and sonar analysis, light detection and ranging (LiDAR) analysis, target identification, and traceability, among others.
- Industrial applications: including computer-aided design and manufacturing, computer simulation in testing and assembly of products, automatic control for quality measurements, and ergonomics.
- Archaeology and anthropology studies: including image processing, radar and sonar analysis, resource management, urban dynamics, and knowledge extraction from remote sensing imagery.

As a definition, pattern recognition is the scientific discipline that focuses on the classification of data, objects, or, in general terms, patterns into categories or classes. To achieve this goal, the methodology is focused on the extraction of information from data observation, learning to recognize the different patterns contained within the data (learning process), and making a decision based on the category of the patterns

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(classification process). This involves capabilities of unsupervised learning, supervised learning, and adopting minimum risk strategies.

A basic process for pattern recognition is statistically based and focuses on the statistical properties of the patterns (i.e., probability densities). The pattern is represented in a feature space, where the features are an object's characteristics usually expressed with numeric data. The classes or categories are groups of patterns having similar values in its features and, according to a given metric, each class has its own model that is its own mathematical description.

The main goal of the pattern recognition process is to hypothesize the model that describes each population class, to process the data to eliminate noise (values that are not providing useful information for the classification process), to choose the model that better corresponds, and to assign it to the class described by that model.

The unsupervised classification technique can be used to partition a large set of data into groups, called clusters, so that the data points in a group are similar to each other, while those in distinct groups are not similar to those in the other groups. This process is usually selected when the datasets are not originally grouped and the quantity of groups within the data is unknown; however, the datasets can be partitioned into distinct groups based on the similarities or distances among the data points.

The supervised classification technique can be used when the classification is based on a given number of groups and the objective is to assign any new data point to one of these groups. For this process, the number of groups is well known and some data from each group are also known and used to characterize each particular group; therefore, once the new unclassified data points are analyzed, the known information allows the definition of a classification rule to assign those points to a particular group.

Classification process

The main process of classification used by pattern recognition methodologies consists of two stages.

The first stage is the recognition of an object's categories. As an example, considering the context of remote sensing images of the land surface, these categories could include woodlands, water bodies, grassland, and other land cover types, depending on the geographical scale and nature of the study. The second stage in the classification process is the labeling of the entities to be classified; for the considered example, these labels are numerical so that a pixel that is recognized as belonging to the class "water" may be given the label "1," "woodland" may be labeled "2," and so on. Therefore, the process of image classification requires performing the following steps:

- To determine a priori the number of categories in which the image will be described. This is the previously described learning process.
- To assign the numerical labels to the pixel on the basis of their properties using a decision rule. This is the previously described classification process.

Moreover, a set of grayscale values for a single pixel measured in a number of spectral bands contained within the remote sensing image is known as the pattern, and those spectral bands that define the pattern are called features. Therefore, a pattern is the set of measurements on the chosen features for the individuals that are to be classified. The classification process is considered as a pattern recognition methodology for this example: that is, the identification of the pattern associated with each pixel position within the image in terms of the characteristics of the objects or materials that are present at the corresponding point.

Supervised pattern recognition

Supervised classification methods are based on external knowledge of the area within the sample to be studied. Unlike the unsupervised methods, the supervised methodologies require some input from the user (or a priori information) before the chosen algorithm can be applied. This input may be derived from different methodologies; as an example considering remote sensing images,

the a priori information could be provided by fieldwork, air photo analysis, reports, or from the study of known maps for the area of interest. The supervised methods are implemented using two main paradigms: statistical algorithms and neural algorithms. The statistical approach uses parameters that are derived from sampled data in the form of training classes—for example, minimum and maximum values of the features, or the mean values of the individual clusters, or the mean and variance matrixes for each class. The neural approach does not rely on statistical information derived from the sample data but is trained directly on the sample data; this is an important characteristic of neural methods because it makes no assumptions concerning the frequency distribution of the data. Statistical methods are known as parametric because they use statistical parameters that are derived from the training data, whereas neural methods are known as nonparametric (Mather 2004).

The supervised classification method requires prior knowledge of the number of classes and, for the statistical classifiers, some descriptive information from those classes is also required. Considering a remote sensing image, the statistical characteristics of the classes that are to be estimated from the training sample pixels depend on the method that will be used. The simple parallelepiped method requires estimates of the extreme values on each feature for each class, while the k-means or centroid method needs estimates of the multivariate means of the classes. The maximum likelihood algorithm requires estimates of the mean vector and variance matrix of each class. On the other hand, the neural classifiers operate directly on the training data but are strongly influenced by the mis-identification of training samples and by the size of the training datasets. The mis-identification of an individual training sample pixel may not have much influence on a statistical classifier, but the impact on a neural method could be considerable.

The a priori knowledge of the number and statistical characteristics of the classes should be reliable and this is a matter of crucial importance for a correct and accurate process. The accuracy of a supervised classification analysis will depend on two factors:

- The representativeness of the estimates of both the number and the statistical nature of the information classes present in the dataset.
- The degree of departure from the assumptions upon which the classification technique is based.

These assumptions may vary from one technique to another; however, the most sophisticated technique will have the most stringent assumptions. Moreover, the validity of statistical estimates depends upon two factors: the size and the representativeness of the sample. The sample size is not simply a matter of “the bigger the better;” it is related to the number of variables whose statistical properties are to be estimated, the number of those statistical properties, and the degree of variability present in the class.

As an example, considering a remote sensing image, in the case of a single variable and the estimation of a single property such as the mean or the variance, a sample size of 30 pixels is usually held to be sufficient. For the multivariate case, the size should be at least $30p$ pixels per class, where p is the number of features (e.g., spectral bands). The classification accuracy tends to improve as the sample size increases (Dobbertin and Biging 1996); therefore, depending on the computer performance available to the user, the sample size can be increased in order to obtain a more robust result. On the other hand, neural-based classifiers appear to improve its performance compared with the statistical approach for small training sets, though better results were achieved when training set size was proportional to class size and variability (Blamire 1996).

Training samples are normally located by fieldwork or from air photograph or map interpretation (for the sample of remote sensing images), and their positions on the image found either by visual interpretation, carrying out a geometric correction on the image, or by geopositioning of the image to be classified. Therefore, a map coordinate will be converted to the corresponding image in column and row coordinates; the location of the image of a training sample whose map coordinates are known is a relatively simple matter, providing the geometric transform is accurate.

The minimum sample size previously specified is valid only if the individual members of the

training sample are independent, as would be the case if balls were drawn randomly from a bag. Generally, adjacent pixels are not independent, for a remote sensing image for example, and if a pixel is identified as “forest,” its neighbor pixel would also be a member of the class “forest.” If those pixels were statistically independent there would be an equal chance that the second pixel was a member of any one of the candidate classes, irrespective of the class to which the first pixel was allocated. The correlation between nearby points in an image is known as spatial autocorrelation. It follows that the number of pixels in a sample is an overestimate of the number of fully independent pieces of information in the sample if the pixels making up the training sample are autocorrelated, which may be the case if a block of pixels is selected rather than scattered. The consequence of autocorrelation is that the use of the standard statistical formulas to estimate the means and variances of the features, and the correlations among those features, will provide biased results. Correlations between spectral bands derived from spatially autocorrelated training data will, in fact, be underestimated and the accuracy of the classification will be reduced as a result. The variance matrixes are considerably greater when computed from randomly selected pixels within a class rather than from contiguous blocks of pixels from the same class. The degree of autocorrelation will depend upon the natural association between adjacent pixels, the pixel dimension, and the effects of any data pre-processing. The degree of autocorrelation can be calculated by taking sequences of pixels that are spaced several units (predefined) apart and plotting the correlations between a set of pixels and their first, second, third, and subsequent nearest neighbors in the form of a correlogram (Basu and Odell. 1974).

Another source of error encountered in the extraction of training samples is the presence in the sample of atypical values. For instance, one or more vectors of pixel measurements in a given training sample may be contaminated in some way; therefore, the sample means vector and variance matrix for that class will be in error. There are some methodologies to detect those atypical values using estimators of the mean vector and variances matrix which are robust; that is, they are not influenced by those atypical values (Campbell 1980).

The performance of a classifier is usually evaluated using measures of classification accuracy. These accuracy measures use a test set of known data that are collected using the same principles as those described above for the training dataset. The training data are used to calibrate the classifier and test data are used for validation (Muchoney and Strahler 2002).

Statistical classifiers

Three algorithms are described in this section; all require the number of categories (classes) to be specified in advance and that certain statistical characteristics of each class are known:

1. The parallelepiped or box classifier, where a parallelepiped is considered as a simple geometrical shape consisting of a body whose opposite sides are straight and parallel. A parallelogram is a two-dimensional parallelepiped. To define such a body all that is required is an estimate for each class of the values of the lowest and highest pixel values in each band or feature used in the analysis. Pixels are labeled by determining the identifier of the box into which they fall.
2. The centroid classifier, which uses information about the location of each class in the p -dimensional Cartesian space defined by the p bands (features) to be used as the basis of the classification. The location of each class in the p -space is given by the class mean or centroid.
3. The maximum likelihood classifier, which also uses the mean as a measure of the location of the center of each class in the p -space and, in addition, makes use of a measure summarizing the disposition or spread of values around the mean along each of the p axes of the feature space.

Neural classifiers

One of the best image interpretation systems is the combination of the eyes and the brain. Signals are received by two sensors and are converted into electrical impulses and transmitted to the brain,

which interprets them in real-time, producing labeled and three-dimensional images of the view field. The brain is composed of a large number of simple processing units called neurons. The number of neurons is in the order of a hundred billion (Greenfield 1997), and each neuron is connected to around 10,000 other neurons (Beale and Jackson 1990). The neurons are connected in complex ways, so that each neuron receives as input the results produced by other neurons, and in turn outputs its signals to other neurons.

The artificial neural networks are based on this model of the brain by building sets of linked processing units in analogy with the neurons of the brain and using these to solve problems. Each neuron is a simple processing unit which receives weighted inputs from other neurons, sums these weighted inputs, performs a simple calculation on this sum such as thresholding, and then sends this output to other neurons. The learning process is accomplished by providing training samples and comparing the actual output of the artificial neural network with the expected output. If there is a difference between the two, then the weights associated with the connections between the neurons are adjusted so as to improve the chances of a correct decision and diminish the chances of the wrong choice being made, and the training step is repeated. This simple model is called a single layer perceptron and it can solve classification problems for pattern recognition applications.

SEE ALSO: Archaeological Classification; Cluster Analysis; Computer Applications in

Archaeology; Databases in Archaeology; Descriptive Statistics; Multispectral and Hyperspectral Imaging; Neural Networks; Remote Sensing; Statistics in Archaeology

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Tripole (Ternary) Diagrams

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Tripole diagrams (also known as ternary or triangular graphs, and phase diagrams) are used in archaeology to aid analysis where three variables are compared with each other, within an equilateral triangle as the basic display medium. The graphical display allows for assessment of a large number of individual cases, either by simple visual means or by sectoral subdivisions within the diagram (Figure 1a).

In order to draw up a tripole diagram, the data need to be standardized, usually to percentages. This has the effect of making the three variables entirely interdependent, with significant implications for the choice of variable to be plotted and overall interpretation of the diagram. Graphing programs are commonly used for creating the diagrams and associated data tables, usually in the form of add-ons to Microsoft Excel, such as Tri-plot (Graham and Midgley 2000), or specialist graphing software, such as the ggtern add-on to R (Baxter and Cool 2016) or SigmaPlot. Traditionally but now obsolescent, printed triangular graph paper was used for hand creation of inked diagrams.

The selection of cases to plot in a tripole diagram needs to be carefully made. Standardization has the effect of giving each case equal weight, regardless of whether the underlying total for each case was very low or high (Steele and Weaver 2002). In practice, two procedures can mitigate this: (1) non-inclusion of any case with a total below a certain threshold (e.g., 200); and (2) use of a system of graded symbol sizes on the diagram to indicate each case total (Figure 1b).

Another issue in the selection of data is that the diagrams work best when all three variables are clearly present, in at least the majority of cases

in a sample. If not, for instance if two variables are dominant and the third only feebly represented, the resulting diagram will place all the cases along or adjacent to the margin of the triangle representing 0 percent of the third variable. This reduces the usefulness of the ternary effect in the plot, and two-variable graphing would usually be preferred.

Interpretation of a tripole diagram is, effectively, a visual process, that is, by observation of where cases cluster or disperse across the diagram. This is akin to examining an x/y scatter diagram visually for clustering, linearity, and so on, prior to further statistical processing. Usually, visual observation is as far as interpretation is taken, for most tripole diagrams, and interpretation takes the form of statements such as “the cases cluster towards the high X percentage sector of the diagram, thus confirming the dominance of X in the analyzed sample.” However, it is possible to subdivide the diagram into predetermined sectors or phases, for instance to define soil or chemical composition, and then to inspect the dispersion of cases and their fit within the various sectors. A more statistical approach is to define means and standard deviations for each of the three (standardized) variables in the sample, and plot the resulting polygon within the diagram. This can highlight differences between groups of cases from different samples plotted on a single tripole diagram. Alternatively, kernel density estimates can be added to the diagram (Baxter and Cool 2016, 126) or likelihood estimates plotted as curves/contours within the diagram (Weaver, Boyko, and Steele 2011).

Usage of tripole diagrams in archaeology is most commonly met with in zooarchaeology, especially where percentages of the three main Eurasian domesticated mammals are being compared—that is, domestic ox, sheep, and goat (usually grouped together), and domestic pig. Examples include comparison between provinces of the Roman Empire (King 1999), or temple assemblages compared with other types of site (King 2005, Figures 2 and 3).

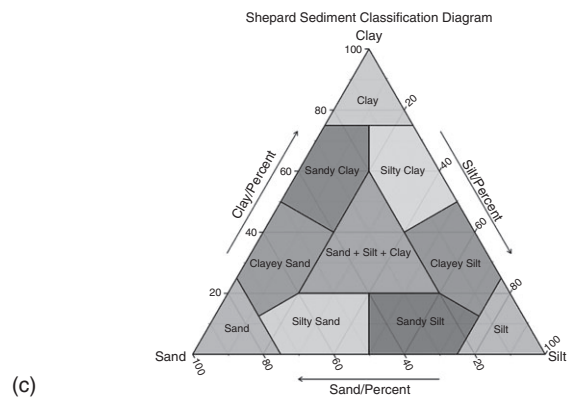
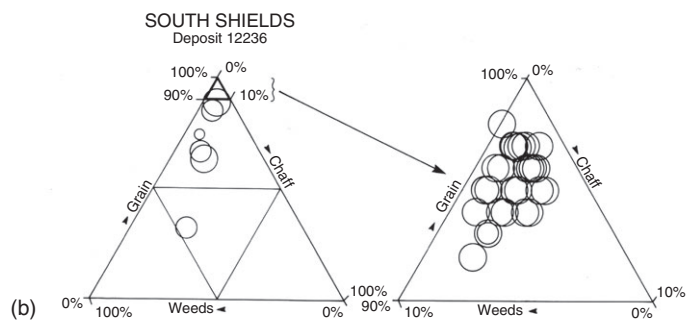
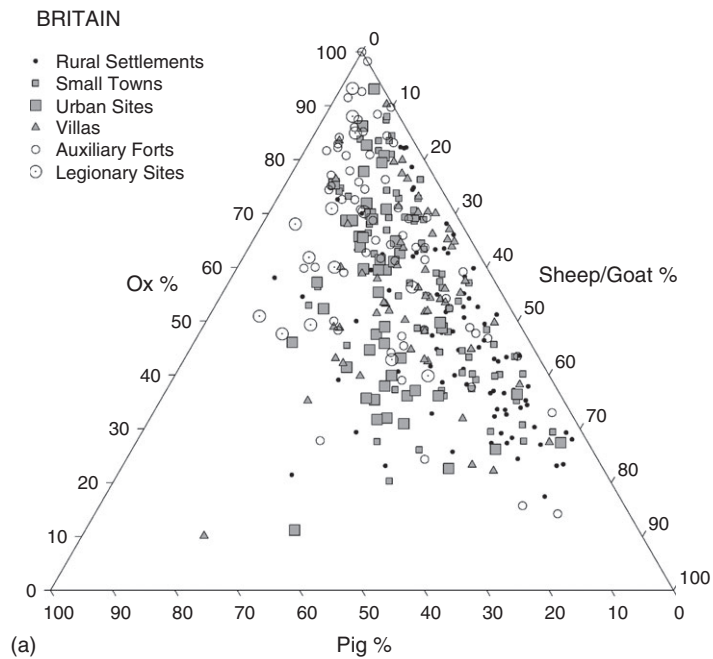


Figure 1 (a) Tripole diagram of ox, sheep/goat, and pig assemblages from Roman Britain, with categorization of type of site. Source: King 1999, Figure 9. (b) Tripole diagram of cereal grains, chaff, and weed seeds from the Roman site of South Shields, the United Kingdom, showing proportional circles relative to the size of each sample, and enlargement of a portion of the diagram to enhance readability. Source: Van Der Veen 1992, Figure 8.4. (c) Blank tripole diagram for clay, silt, and sand percentages, showing a scheme of phases for definition of sediment types. Source: N. Hamilton, <http://www.ggtern.com/wp-content/uploads/2014/07/plot.png>.

Other uses within zooarchaeology include intrasite analysis of assemblages, mortality profiles (Steele and Weaver 2002; Weaver et al. 2011), and comparison of representation of body zones in a single species. In paleobotany, tripole diagrams have been used to plot grain:chaff:weed ratios in archaeological samples (Figure 1b).

Another common usage of tripole diagrams is in archaeometallurgy and chemical compositional analysis, for instance to compare gold, silver, and copper ratios in metal artifact surface composition (Baxter and Cool 2016, 127–129) or copper alloys (Roxburgh et al. 2016, 416). It was in this area of science that tripole diagrams were effectively first developed (Howarth 1996). A third area of application of tripole diagrams is in geoarchaeology, especially soils and sediment analysis, where it is used, for instance, as an aid in “finger-texturing” soil samples (Jones 2007, Figure 29) (Figure 1c). It is largely from these branches of the earth sciences that the impetus came for the take-up of tripole diagram methodology more widely in archaeology in the mid-twentieth century.

The advantage of creation of a tripole diagram is that large datasets with three variables can be displayed and samples easily compared. Attention, however, is needed in the selection of material to be compared in this way, because of the interdependence of the standardized data. Encouragingly, there are now increasing signs of utilization of this graphing technique in artifact assemblage analysis, as well as the archaeological science applications outlined above (Baxter and Cool 2016, 120–122).

SEE ALSO: Bioarchaeology; Characterization of Metals and Alloys; Exploratory Data Analysis (EDA); Geoarchaeology; Soil Survey;

Zooarchaeology; Zooarchaeology and Human Diet Reconstruction

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Action Theory

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Overview

One of the central problems of archaeology as a “human science” is the nature of human action. What might be thought of as essentially sociological, psychological, or philosophical questions about human intentionality, individuality, socialization, and so on become distinctively archaeological when considered over the breadth of times, places, and societies that the discipline deals with. Two important aspects of these questions, from an archaeological perspective, are the degree to which there are universal modes of human engagement in the world, and the role that material culture plays in mediating or shaping the ways in which humans act. Each of these sets of issues in turn leads on to other crucial questions to do with the distinctiveness of humans vis-à-vis other species, and the ways in which seemingly inanimate entities—everything from the wind to a computer—can be said to “act.” Archaeologists need to consider such issues not only because the archaeological record is primarily a record of human action, but also because answering some of these latter questions has the potential to offer profound insights to a wide array of other disciplines. Thus, these sorts of issues frame much of the relevance archaeology has in the contemporary world. Like many such foundational issues, however, archaeologists have only relatively recently opened them up to serious debate; prevailing approaches for much of the history of the discipline were rather limited. The next sections review these earlier approaches before delineating the contours of current debate.

Early approaches to action in archaeology

The practice of archaeology in the nineteenth and early twentieth centuries lacked an explicit theory of human action, even though this period—in the diverse manifestations of Marxism and phenomenology, to name but two of the relevant intellectual movements—was the heyday of philosophical approaches that would later be highly influential. The most coherent and timely theoretical agenda in archaeology of the later nineteenth century was evolutionism, but this was very different in substance to later phases of evolutionary theory in archaeology, and dealt primarily with very broad social groupings rather than the details of individual activity. In the early twentieth century, with the coalescing of the “cultural historical” school of archaeology across Europe and North America, a more particularistic focus on the definition of individual cultures did develop. However, this again largely ignored the issue of human action as in any way problematic, instead defaulting to a “normative” view that people’s activities were implicitly characteristic of the ethnic or social group of which they were members. This developed in parallel with functionalist sociology and anthropology of the same period, which tended to stress forces promoting social conformity. The beginnings of an agenda allowing for freedom of action, and thus the role of human actors in creating social change, began to be evident in the Marxist-inspired work of V. Gordon Childe, but this did not flourish in the cultural climate of post-World War II UK and US archaeology (though it did elsewhere in the world). Rather, in the 1960s especially, an evolutionary approach reemerged, which paid some attention to the mechanics of human activities but primarily through the lens of what might be more or less adaptive *behaviors*. The significance of this latter term, as distinct from “actions,”

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is that it indicates an approach to interpreting human (or animal) activity with reference only to externally visible characteristics and thus without reference to “inner” thought processes (Shanks and Tilley 1992, 55–56). It is thus characteristic of the whole series of approaches considered so far which, in their own distinct ways, privileged “objective” entities—social groups, observable behaviors—over “subjective” ones. Only with the explicit introduction into archaeology of theories dealing with the latter, in the 1980s, can we say that the discipline began to deal with human action in a meaningful sense.

Agency debates from the 1980s to today

Much of the discussion taking place in archaeology since the beginning of the 1980s about the complexity of human action, and the relationships between thoughts, activities, social groups, and artifacts, has been conducted around one key term: “agency.” While its meaning is notoriously malleable (Dobres and Robb 2000), this word has traditionally been used in social theory to refer to the human capacity for action which is at least potentially intentional and knowledgeable—that is, involving some degree of free will, but also conducted in a context of socially established conventions of how to act appropriately. Embedded in this concept, then, is a cluster of complex issues to do with the nature of human consciousness and embodiment, as well as the connection between what goes on in an individual’s cognitive experience and the social world around them. While it is easy to characterize this as essentially a debate over individual freedom versus social determinism, a long tradition in social theory has sought to articulate the problem in more nuanced terms. Archaeologists began to incorporate some of this work into their theoretical frameworks in the 1980s, along with other related ideas about the meanings of material culture and the political dimensions of the past that, collectively, came to define “post-processual”/“interpretive” archaeology. Most prominent in the reference points for early explorations of agency, and its companion term “structure” (referring to social formations/institutions), were the works of social theorists Anthony Giddens and Pierre

Bourdieu, both working creatively with the traditions of structuralism and Marxism, among others. Both scholars, in distinctive ways, sought to understand the mutually constitutive relationships between “agency” and “structure” in shaping human lives. Both stressed the concept of “practice” as the medium through which these relationships unfold—the balance between individual volition and social influences being manifest in all human activities to different degrees. Archaeologists deployed these insights in various ways, though also soon began to develop and critique certain aspects of them. From the outset, there were debates not only about the intricacies of different models of human action, and the effectiveness of their archaeological application, but also about the key question of universality of human experience across time and space (Johnson 1989). Through the 1990s and into the 2000s, as archaeologists continued to work with agency, structure, and practice in detailed case studies while developing different views on this question (see, e.g., Dobres and Robb 2000; Gardner 2008), the general notion that past agency was an important topic began to become fairly mainstream. From this point to today, though, the terms of debate have shifted as challenges to practice-based approaches have emerged from two different directions: evolutionary theory and post-humanism.

Approaches in contemporary evolutionary archaeology are distinct from both of the earlier major phases in the development of this tradition in several ways, but most relevant here is their attention to processes of cultural transmission—the ways in which patterns of activities (e.g., pottery-making) are passed on over time. The preferred approach to modeling these processes is in terms of neo-Darwinian theories dealing with variation, selection, and adaptation. As a perspective on human action, therefore, this can perhaps be aligned with previous trends in archaeology which paid less attention to conscious decision making and more to underlying forces in driving the ways in which individual humans act. This has led to some significant debates between the interpretive and evolutionary schools in archaeology in recent years (e.g., Kristiansen 2004), which often recapitulate earlier post-processual–processual divides about whether particularistic/emic or generalizing/etic

interpretation is more fruitful or viable in archaeology. It is worth noting, though, that the way in which practice theories approach the largely unintended reproduction of social structures is somewhat similar to the notion that individual actions might also have long-term adaptive significance, and this reminds us that a crucial question in both approaches is the nature of the connection between small- and large-scale phenomena. However, a more challenging aspect of some evolutionary archaeology has been the suggestion that the units of selection (the “memes”) might be the real drivers of cultural change, with humans being mere vectors for the reproduction of pottery styles and the like. Interestingly, the idea that types of pots might have more “agency” in their transmission than the humans making them intersects quite closely with the other major emerging school of thought on action, inspired by quite different intellectual trends that can loosely be described as “post-humanist.” Like evolutionary archaeology, this is a diverse movement and incorporates work variously inspired by figures in anthropology (Alfred Gell) and science and technology studies (Donna Haraway, Bruno Latour), among others. The broad program is to overturn the purported anthropocentrism of previous archaeology and accord more “agency” (and/or “personhood”) to other species, and to the object world, often by distributing action among networks of entities (e.g., Gosden 2005). There are some further similarities here with evolutionary thinking, which also ultimately seeks to downplay the “specialness” of humans that more traditional social theories are said to assume (though this point is contested; see later). Since these post-humanist/“new materialist” approaches have advocated a distributed or generalized model of agency, it seems that future directions in this area will be defined, as they were 20 or so years ago, by the question of what does—or should—“agency” mean?

Future directions

Theories about human—and nonhuman—action address central problems in our understanding of the past and relate quite crucially to the role of archaeology in the present. They connect the

discipline to a wide range of other fields across the social and biological sciences. Necessarily, therefore, it is unlikely that some of the major debates touched upon here will be definitively resolved at any point soon. There is considerable scope for new alignments in archaeological theory to replace those that have dominated the discipline since the 1960s, based on some of the conjunctions mentioned above in evolutionary and “new materialist” approaches. There is also great potential for some as-yet untapped theoretical traditions, such as the pragmatist/symbolic interactionist school of social theory, to find fuller development in archaeology (Baert and Carreira da Silva 2014). Yet it remains necessary to keep debating the core issues and identifying the strengths and weaknesses of different traditions without oversimplifying or caricaturing different positions, something that has unfortunately dogged theoretical discussion in archaeology since the 1960s. At the time of writing, some of the claims of the “new materialist” approaches about “humanist” archaeologies of agency are being challenged or rebutted (e.g., Barrett 2014; Ribeiro 2016), and this debate, rather than the creation of a new orthodoxy, is probably healthier for the discipline. Indeed, archaeologists could do worse than apply different theories of action to themselves and to the creation of knowledge in contemporary contexts of practice, to enhance disciplinary reflexivity and consider how archaeology might most effectively develop in the future.

SEE ALSO: Behavioral Archaeology; Critical Theory; Evolutionary Theories; Material Entanglement; Mind and Cognition; New Materialisms; Perception and Experience; Personhood and Objecthood; Symmetrical Archaeology; Time and Temporality

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Archaeological Fieldwork

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Fieldwork is practical research conducted in the context of a site or a landscape. It is multidisciplinary and comprises a range of techniques and methodologies that may be utilized in the identification, recovery, and recording of archaeological data. Archaeological fieldwork is most often directly equated with excavation—a range of techniques that provide an intrusive entry into an archaeological resource, and which is perceived to distinguish archaeological fieldwork from that pursued in other sciences. However, there are a multitude of non- or less-intrusive techniques in archaeological fieldwork (such as differing forms of ground or aerial survey) that share methodological bases (and origins) with other sciences.

Fieldwork is a blend of investigative standards and innovative practice. Commitment to a methodological strategy, for example, may require recognized techniques modified as appropriate to particular circumstances of fieldwork, such as in response to the characteristics of a site's topography and its geology; the quality and scale of archaeological preservation; the logistics of a site's geography, including its sociopolitical context; and the nature and scale of a project's specific research priorities, expectations, and financial resources. Basic methods remain similar to the origins of fieldwork, but are greatly enhanced by the depth and detail of scientific techniques and experience of expertise. The relationship between fieldwork (as the recovery of data) and theory (as the interpretation of data) is conceived in a number of ways that, rather than simply reflecting historical advancement across the discipline, are a result of the multiplicity of conceptual frameworks through which archaeology is practiced and understood today.

The origins of fieldwork as a practice performed by scientists may be found in the

activities of naturalists and geologists in the later nineteenth century, as well as in antiquarian studies. Similar to the collection of specimens, excavation was simply a recovery method for items of material culture and supplemental to topographic survey. Disciplinary advancement emerged through analysis of collections by individuals not necessarily engaged in the attribution of specimens through fieldwork. As a consequence, a broad distinction emerged between the intellectual pursuit of collections and the practical collation of specimens in the field. Where written records may not have sufficed, the cultural progress of humanity could be traced in the stylistic and typological developments of material collections; understanding the evolution of human society owed little to the specific qualities and character of individual sites.

Archaeological conceptions of human cultures through principles of evolution may account for the limited status assigned to fieldwork in the nineteenth century (Lucas 2001). Emphasis was instead placed upon material collections and their classification into a universalized scheme. Emergence in the early twentieth century of a particularistic conception of human cultures, such as the historical assemblage of areal cultural groups, established the importance of objects' spatial and temporal context, and thereby enhanced fieldwork as integral to archaeological analysis. Primary to the concern of culture history were questions of what, where, and when? Greater standardization of data collection via fieldwork was a requirement for comparison of material assemblages across cultural groups. It is therefore not coincidental that in the first half of the twentieth century a growing number of field manuals emerged that defined standards and methodological principles required for scientific archaeological fieldwork. By the 1960s, the solidity of these principles and the questions for which they were developed underwent a radical transformation, most notably as a part of the "new archaeology" (or processual archaeology) in which fieldwork was aimed towards questions concerned more with how and why cultural changes take

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place, rather than simply recording the traits that determine cultural definition. Advocates of this approach argue that archaeological data from particular regions contains information necessary to identify and to study the complex systems behind cultural processes, such as regular patterns of behavior; however, the visibility of relevant information is inhibited by a lack of statistical control during fieldwork (Binford 1964). Isolating the kind of data required to solve this problem may therefore be achieved via appropriate sampling strategies designed specifically for hypothesis testing against the immediate and unique circumstances of data recovery. This is a reflexive process in which feedback from data analysis leads to the modification of the sampling strategy during subsequent fieldwork.

To the philosophical traditions of culture history and processual archaeology common methods and aims are desirable to the development of a unified discipline in which data recovery might facilitate intersite or cross-regional comparison. Indeed, many of the principles that have emerged from this goal lie at the core of field research design. Ideally, this is a structuring framework conducted with a procedure that includes reconnaissance (survey and background research), evaluation (intrusive sampling for site characterization), strategy planning and excavation (method of data identification and recovery), and analysis of data upon which future strategies may be modified (Carver 2011).

Across a number of European nations, as well as North America, Australasia, and Japan, the majority of archaeological fieldwork has functioned within the framework of development and its attendant planning legislation. This is a reactive process, carried out in response to individual development, and requires assessment of the archaeological character and significance of the area affected by a proposed development and the likely impact that this may incur. This has led to numerous and major archaeological operations, sometimes on a substantial scale. In general, the same procedures of field research design outlined above are implemented, but the exposure of enormous areas far greater than was previously possible has allowed for detailed reflection as to the success of evaluation and sampling methodologies.

Owing to the competitive nature of open-tender contracts in development-led archaeology, pragmatic constraints often posed by limited time and financial resources, and perhaps also as a response to its expanded professional status, a degree of standardization in fieldwork methodology has emerged. On the one hand, this provides a baseline against which to adjudge the quality of archaeological investigations; on the other hand, sampling strategies designed to locate the anticipated presence of particular features of a site are constrained with bias towards these types of site. Instead, by employing a spirit of experimentation and innovation, particularly in sampling exercises, fieldwork may with greater accuracy determine the appropriate levels of work required on these sites.

A recent example of experimentation and refined sampling methodology is found in Cambridgeshire's fenland in the United Kingdom (Evans, Tabor, and Vander Linden 2014). This comes from a large decade-long investigation of a series of small riverine islands sealed by thick overlying strata, excavated in advance of their destruction by aggregate quarrying. In this situation, particular conditions of burial had ensured that archaeological deposits survived in great quantity in sealed paleosols (ancient land surfaces) and overlying ploughsoil. The scale of these residues presented challenges of strategy and prioritization. Whereas cut features were comparatively limited in their numbers, tens of thousands of artifacts were encountered throughout the thick, sealed paleosol. Differing complementary techniques were employed at different stages of the fieldwork in light of incremental experience gained in ongoing methodological experimentation. This was not simply employed to achieve maximum data recovery (total recovery would have been an impossibility, given the scale of the finds numbers and ground coverage compared with available resources); the aim was to answer specific questions so as to avoid the repetition of preformed assumptions about past behavior and long-term cultural development. In this instance, where the scale of past activity is matched by the intensity of investigation, a distinct "narrative" was gestated during the immediacy of fieldwork, and ultimately framed by particular ways of (and reasons for) thinking and doing.

Reevaluation of fieldwork has, since the 1990s, centered upon the connection between theory and practice, or thinking and doing. Like the example above, this has expanded upon discussions concerning sampling in fieldwork and its implications to an understanding of archaeological data by problematizing the assumption that fieldwork is an objective activity and that its primary function is the acquisition of data separate from and prior to the processes of interpretation and writing “narratives.” Drawing insight from philosophies of science, two important themes have emerged in contemporary debates concerning fieldwork: (1) First contact with the material traces of the past takes place within the field and is an interpretative practice; and (2) fieldwork takes place in, and is a part of, a material world that channels practices of interpretation. These themes are outlined below.

A key aim has been to foreground fieldwork as a practice and an experience that has a significant—indeed, founding—role in the production of knowledge. The fieldworker is foregrounded as central to this reevaluation, and viewed as partaking in a dynamic and subjective encounter with residues of the past (Hodder 1999). In the immediacy of this encounter, the fieldworker’s craft greatly relies upon a developed sensory register that is learnt through practice, such as an ability to “read” the traces of past occupation in a landscape’s lumps and bumps, anticipating a subtle change in a soil deposit through its appearance and the texture of the grain, or recognizing material by its weight, size, and form. Such skills develop over time and through experience, and are applied together with a multitude of factors (e.g., related deposits and other archaeological features; the accumulation of data from elsewhere on a site) to make informed judgments that determine what is archaeological from the nonarchaeological, and to distinguish relevant data from what is often highly fragmented and mixed traces.

Highlighted in contemporary philosophical debates concerning fieldwork is that archaeological data is not necessarily predetermined prior to its recognition in fieldwork, awaiting its discovery. This challenge emerged from a broader concern in post-processual archaeology: that knowledge is not discovered out of neutral evidence, but is instead a product of social and

political conditions through which the practice of archaeology is constituted. According to this principle, fieldwork is not simply an exercise in data recovery and collection, but by mobilizing an assembly of different material bodies and agencies it is active in the production of data (Lucas 2012). Within these contemporary views of fieldwork, the production of data is contingent upon innovation in the strategies, techniques, and technologies available for their identification, recording, and recovery.

Another example of large-scale investigations in the United Kingdom illustrates the integration of a number of these principles at the heart of field research design. Carried out before the construction of a new terminal at Heathrow Airport, fieldwork was conceived around the premise that changes in material conditions at any given location made the living of varied kinds of life a possibility (Andrews, Barrett, and Lewis 2000). Communities across time inhabit places that already have a history with which past communities would have had to contend in different ways at different points of time. This was a driving theme throughout the field research design. During fieldwork, excavation staff worked with an integrated site database examining historical changes of the “natural” and “built” environment, and the character and effect of long-term formation processes on these, as well as the material expression of human response to the accumulation of these factors. The field research design facilitated preliminary and rapid site-based analysis and feedback and the development of a site “narrative” through field-based interrogation that could be further refined through off-site analysis: a dialogue between on-site and off-site analyses. Accepting the fragmentary nature of the archaeological record and the status of data as a product of interpretation, the visibility of data redundant to the emerging narrative could be defined.

An accompanying argument to the production of data through acts of interpretation is that the fieldworker is bound within the larger assemblage of material and conceptual entities, and is materially constituted as a field practitioner by an ability to mobilize an array of tools for recognition (trowel, toothpick, brush, etc.), measurement (measuring tape, grid peg, electric distance meter, etc.), and recording (pencil, camera, 3D scanner, etc.) of archaeological data. These materials are

part of a broader collective, the status of which, and their relationship to archaeological narrative, may differ depending on their combination and on their context of assemblage. The site archive has been provided as a particular example of this, and a further illustration of the material world relevant to fieldwork (Olsen et al. 2012). In this frame, the archive is the stabilization and collation of an otherwise fragmented record by means of a range of media, such as digital and film photographs, soil and organic samples, drawn sections and plans, digital spatial data and imagery, finds, and accompanying paper registry, including notes, diaries, and correspondence. The archive may be regarded as a representation of a site or the act of fieldwork, or it may be described as a “translation” (Lucas 2012); that is, the replacement of one material entity (a potsherd within a pit, for example) with another material form (a digital or hand-drawn plan and drawn section with photographs of the pit, along with a washed potsherd, perhaps illustrated, bagged, numbered, boxed, and catalogued in a register). As a dislocation of things from their context of discard and discovery, the archive may be regarded as a process of loss; but in viewing the archive as a material entity in its own right, the process of dislocation during and after fieldwork may also be viewed as the inscription of new meaning open to interpretation.

Fieldwork is a collaborative operation that involves a collective of people, materials, instruments, settings, and agencies. These combine to both enable and constrain the conduct and remit of fieldwork, and perhaps also in some cases the direction of fieldwork narrative. Differing agencies may authorize, accredit, and legitimize fieldwork. Permissions, standards, guidelines, and financial commitments are implicated in the fieldwork process via consultation with communities, local authorities, government ministries, heritage bodies, donors, lenders, or grant-awarding bodies, as well as academy and industry representation. Fieldwork is therefore not practiced outside of society, but is firmly integrated with the complexities of its problems and possibilities.

As much as fieldwork is conducted within the network of broader society, so too is it a social practice that encompasses a collective of multiple voices. The use of new media, onsite databases,

and individual field diaries has been integrated into a number of field research designs as a means to record processes of interpretation and documentation, both of individual and collective fieldworkers, these ephemeral moments otherwise being lost. Highlighting the collaborative nature of fieldwork entails an ethical motive, aimed towards a democratization of the interpretative process, from the ground up. The issue of multivocality in fieldwork has strengthened the growth of community-led initiatives that have emerged through concerns regarding the social value of archaeology and the ownership of narratives about the past, particularly in local settings. Development of these issues in field research design has benefitted greatly from postcolonial discourses. These have focused upon the value of fieldwork in contexts where local participants belong to cultural backgrounds notably different and largely incommensurate with that of the fieldwork team. A range of narratives arising by host and guest during fieldwork may reflect different views on the nature of heritage or distinction in the value placed upon archaeology and the priorities to which it may contribute.

An example of fieldwork conducted with one of Kenya’s Samburu communities illustrates an instance in which collaboration that embraces such differences of view can lead to innovative outcomes of knowledge production (Straight et al. 2015). This comprised the excavation of a stone burial cairn by a team of international scientists and the local community, structured through a triage study of cultural, biological, and archaeological anthropology. It was found that the event of the excavation itself, as well as the gradual revealing of the site’s excavated contents, inhabited a range of competing priorities among the team and the broader community and, importantly, generated a variety of open-ended narratives, included in which was the challenge of articulating the complexities of the fieldwork in a range of formats, including publication.

SEE ALSO: Archaeological Record; Assemblage; Burial Excavation; Digital Media in Archaeology; Experiment in Archaeology; Field Survey; Heritage: Nonwestern Understandings; Heritage and Community Archaeology; Interpretation; Philosophy of Science; Sampling Theory; Statistics in Archaeology; Value or Significance

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Archaeological Record

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The recurrent use of the term “archaeological record” may have originally come to archaeology via geology and paleontology, although in the nineteenth and early twentieth century a variety of terms including both “source” and “record” were used interchangeably. Indeed, the transference of more broadly literary or textual concepts to characterize all histories from the earth, including archaeology, was common practice in the nineteenth century. Referring to material remains—whether fossils, rocks, or artifacts—as documents, archives, testimonies, records, and sources was a standard device and one which remains with us today. Yet within nineteenth-century archaeology, there remained a tension between an archaeology which drew its legacy from antiquarianism and history and an archaeology which was more closely aligned with the emerging sciences of geology and paleontology. This division more or less mirrored the division between a historical archaeology which drew its framework from the written sources (i.e. biblical, classical, and medieval) and the new prehistory, the latter of which opened up deep time and brought in the three-age system. Although no longer oppositional as they once were, this division still arguably influences the current topography of archaeology.

It is against this backdrop that we can understand the two major conceptualizations of the archaeological record as they exist in archaeology today: source criticism and formation theory, both of which crystallized as distinct bodies of theory in the 1950s, though both of which had roots extending deep into the late-nineteenth century. *Source criticism* emerged most strongly in Central Europe and Scandinavia and was pioneered by the German archaeologist Hans Jürgen Eggers (Härke 1997; Kristiansen 1978; 1985). He drew explicit analogies between archaeological

finds and documents and, following source criticism in history, distinguished between external and internal criticism. The former, also called textual criticism, concerns the transmission of the source and its representativity, which archaeologists can control to some extent through fieldwork and sampling methodologies as well as attention to issues of preservation. Internal criticism however, was for Eggers of much greater concern because it pertained to historical interpretation. He argued that archaeological evidence was not a face value reflection of people's everyday behavior in the past but was often mediated by their beliefs and ideology and could thus give a false impression if read as such. Internal criticism is also linked to another key distinction in source criticism, between accidental and intentional sources (Härke 1997).

Formation theory in contrast is largely a North American development and is conventionally traced back to the work of Robert Ascher, who characterized the problems facing archaeology as twofold: missing evidence and how to interpret what does survive. However, it is Michael Schiffer who is most associated with the development of formation theory (Schiffer 1987). Schiffer's approach moved beyond the simplistic reductive view of formation processes, as exemplified in Ascher's theory. In that view, the problems were often perceived as largely quantitative—i.e. a loss of data—whereas Schiffer was arguing for the importance of qualitative changes to the record, largely due to differential discard practices and post-depositional processes. Such processes are not solely reductive but also additive and can introduce new patterns into the record. Schiffer catalogued an extensive array of such processes in his work, which he also famously divided into cultural and natural; or c- and n-transforms. In many ways, formation theory has retained its focus on the issues first identified by Schiffer, particularly processes of abandonment and discard or processes which delayed discard, such as curation and use-life (Shott 1998).

The distinction between these two traditions of thinking about the archaeological record should

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not be confused with the distinction between a physical and textual model of the archaeological record proposed by Linda Patrik in her key paper on the topic (Patrik 1985). The physical model, according to Patrik, asserts that there is a causal and physical connection between past events or processes and the record itself—the prototype being the fossil record. The textual model on the other hand asserts that the record encodes information about the past, the prototype being a historical document. Patrik's paper was largely a review of the then current theoretical positions in Anglophone archaeology, the two models reflecting the different perspectives of processualism and post-processualism respectively. While the physical model can be equated with formation theory, the textual model only vaguely maps onto source criticism and there was certainly no genealogical link between the two. Patrik's review paper however is interesting on other grounds, particularly for highlighting the various meanings of the term "archaeological record" as used in the literature. She identified five different meanings used by archaeologists. The first is the material context in which past events or processes occurred—in short, what is variously called the "ethnographic past" or the systemic context. The second and third meanings refer respectively to the material deposits and material remains left behind by these past processes; the fourth concerns the part of these remains recovered by archaeology (i.e. the sample) and the fifth, the record archaeologists themselves create of these remains (i.e. archives, reports).

In many ways it is the interrelations between all these meanings that is significant and is the basis of Lucas' in-depth study of the archaeological record (2012). His book condenses Patrik's list from five to three and examines the productive tensions of juxtaposing the threefold idea of the archaeological record as material culture, as traces or residues of past events, and as the archaeological work conducted on those traces. Drawing on a diverse body of contemporary theory from actor network theory to the new materialism, Lucas argues that what holds these three different dimensions of the archaeological record together is processes of materialization and dematerialization. Lucas' subsequent work also explores other tensions and divisions within our understanding of the archaeological record,

notably the distinction between concepts of the fragment and the residue (Lucas 2014).

Various words have been used to characterize the nature of the archaeological record: remains, vestiges, ruins, relics, traces, and fragments. The list could go on, but by looking at the words we use to define the stuff that makes up the archaeological record in this generic sense, one can discern an underlying tension between two broader concepts, that of incompleteness and that of untimeliness. The idea of the archaeological record as incomplete or fragmentary runs through archaeological discourse since the inception of the discipline (Burström 2013) and its origins can perhaps be traced to Romanticism and art history through the concept of the ruin. The power of the fragment lies in evoking or underlining an absence or loss and, as such, initiates a discourse on the relation between the fragment and the missing parts or between the fragment and the whole. Now, of course, this is inevitably entwined with time, but by emphasizing the fragmentary, time is colored in a very specific way and is conceived as a gradient of diminution or reduction. The whole pot reduced to a few sherds, the pristine sword corroded to a rusty, flaky stick of iron. Indeed, precisely because these are strongly material properties we can directly experience, it is perhaps unsurprising that they are metaphorically extended to define the whole archaeological record.

Arguably the idea of incompleteness has very much dominated our conception of the archaeological record since the late-nineteenth century. Classic statements of this conception emerged in the middle of the twentieth century—formation theory, sampling theories, and source criticism, all of which stressed the loss of evidence or data in the form of a failure to survive—whether this is organic materials or ephemeral phenomena like behavior itself. Moreover it is not only the nature of the archaeological record that is conceived primarily through the notion of the fragment, it is also the nature of archaeological practice. The idea of practice being guided by incompleteness is evident throughout the history of the discipline through the ideal of the total record. Beginning in the late-nineteenth century with German classical archaeology, which stressed the need for a full recovery of all remains not just the fine art specimens and the aspiration for complete collections

of material for analysis, these ideals carried through into the late-twentieth century and its idealization of the archive objective—that the archive should stand in for the site itself. Of course the ideal of the total record was always ambiguous and perhaps seen as an impossible ideal. Yet this ambiguity played to the heart of the issue of incompleteness because it was always about mediating the relation of fragment to whole.

While the idea of incompleteness and the metaphor of the fragment is a powerful way to think about the archaeological record, it lacks an integral temporal dimension. This is not to suggest it cannot be aligned with time, only that time becomes secondary and therefore mediated by the idea of incompleteness, hence the dominant connotation of loss. By contrast, terms such as residues, relics, or vestiges conjure up a rather different image of the archaeological record. Such remains may indeed even be complete or whole; what defines them is not so much their incompleteness but their *untimeliness*; they are from another era, anachronisms, survivals. This conception of the archaeological record in fact may have been the more dominant one in the nineteenth century, only superseded in the twentieth by the metaphor of the fragment. Such a view is very clearly expressed when one considers the close relationship that existed between material remains and what came to be called survivals, that is extant customs or practices which no longer have any obvious purpose, like vestigial organs. In fact up to the middle of the nineteenth century, the word *antiquities* was commonly used to refer to both.

What makes relics and survivals significant then is their *non-contemporariness*. This articulation through the concept of the contemporary is very apposite because it immediately resonates with the oft-repeated statement that the archaeological record is a contemporary phenomenon. This contradiction is particularly troubling, for on the one hand, archaeological remains *are* contemporary—they exist here and now and they are what we engage with, even if our objective is to wrestle out a story about the distant past. At the same time, they are also of or from the past, and not simply in the sense of having persisted or endured in a neutral, chronological sense, but they have persisted into a time in which they do not seem to belong. That is the crux of the

concept of survival: an anachronism, an object or custom out of its proper time. Of course this begs the question of what constitutes the “proper” time for an object and no doubt archaeology itself has helped to create the perceived proper temporal order for things, but more generally this is probably the legacy of modernist thinking insofar as the trope of modernity defines the very possibility of something being untimely. What it underlines though is the way time is critically implicated in our understanding of the archaeological record and how we conceptualize time deeply affects how we think about that record.

SEE ALSO: Archaeological Fieldwork; Assemblage; Behavioral Archaeology; Ethnoarchaeology; Formation Processes; Knowledge and Inference; Material Culture; New Materialisms; Philosophy of Science; Sampling Theory; Time and Temporality

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Archaeologies of Technology

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“Technology reveals the active relationship between man and nature, a direct process of his existence, consequently of the social relationships of his life and so of the general spiritual phenomena that arise from them” (Marx 1867).

“Technology is a science, and because technical facts are facts of human activity, it is a human science, a branch of anthropology” (Sigaut 1994, 422).

Technology—as distinct from *techniques*—may be the material artifacts that humans and some nonhuman animals make and use, the built architecture with which they embellish spaces and places, and in which they dwell and work. It may be also the various ways and means through which people and animals communicate, both oral and written, and the digital media technologies—as representation-based languages—that are embedded in the global technologies of modern capitalism. Some societies routinely engage technologies of conflict and violence, technologies of political and religious authority, and modern reproductive technologies that intervene in the biological cycles of humans, animals, and plants. All these forms of technology are integral to social life in order to facilitate particular actions and practices, to enable discourse. The extent to which social life takes place through technological means has long been a focus of science and technology studies (“the turn to technology”). The theoretical significance of these debates to sociocultural anthropology and archaeology has become increasingly apparent.

For archaeologists, defining technology is not as straightforward as it was in the days of functionalism and culture history. Since the mid-nineteenth century publication by Boucher

de Perthes concerning the first Paleolithic tools (hand axes) found in the Somme river valley, France, the material residues of past technological practices were regarded as more or less self-evident and easily understood through inferential thinking. For example, discussing his “ladder of inference” approach in relation to prehistoric technology, Christopher Hawkes argued: “To infer from the archaeological phenomena to the *techniques* producing them I take to be relatively easy. The modes of research are themselves no doubt difficult, and in detail often tedious. But the reasoning employed, I maintain, is basically simple” (Hawkes 1954, 161). In other words, the connections between the observed material record and the past processes that produced that record are relatively unambiguous because they can be inferred through uniformitarian assumptions about the nature of the relationship between process and residue. A basic example of this is the relationship between the physical properties of flint that allow knappers to predict accurately specific fracture patterns, and the resulting composition of debris and debitage left by the knapper’s actions. Through this assumption of uniformitarian predictability, past manufacturing techniques can be studied through, for example, the experimental replication of stone and bone tools, pottery, and other objects. The publication of Russian archaeologist A. A. Semenov’s *Prehistoric Technology* (1957, trans. 1964), which combined such replication experiments with contemporary ethnographic observations and the microscopic analysis of artifact surfaces (use-wear), allowed archaeologists to observe and describe techniques of artifact manufacture and use. This general methodological approach to past technological processes resonated well with Lewis Binford’s influential ethnoarchaeological research into modern hunter-gatherers, which examined the technological processes by which humans manufactured stone tools, and procured, killed, and butchered animals. The material culture patterning generated through these technological activities allowed Binford to make inferences about past human behavior and animal exploitation strategies.

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While this approach opened up a new field of hunter-gatherer technology-related research, it was criticized at the time for being entrenched in problematic uniformitarian assumptions. So, while the new/processual archaeology shifted the discipline's methodological parameters on technology by moving into ethnoarchaeological inquiry, the primary focus remained, as with the culture history approach, on the purely utilitarian, mechanistic aspects of technology and material culture. In this way of thinking, technology/material culture was analyzed as a subsystem or component—alongside economy, religion, social structure, and so on—within the totality of the larger sociocultural system.

It has been argued that a conceptual break with the cultural historical and processual views of material culture/technology as an “extrasomatic means of adaptation” was marked by the early 1980s advent of post-processual archaeology. In an article first published in 1989, Christopher Tilley argued that the conception of material culture as a system of signification largely came about through (mainly British) archaeological theory's encounter with elements of linguistic and anthropological structuralism, first discussed in any detail in Ian Hodder's 1982 edited volume *Symbolic and Structural Archaeology*. Tilley focused on the potential for material culture analysis of Saussure's early-twentieth-century structural linguistics, which distinguished between *langue* (a system for conveying meaning through rules and functions) and *parole* (speech, the individual use of language) to reconceptualize archaeology “as being a pursuit of sign systems” (Tilley 1989, 188). The analogy with language and linguistic structure not only allowed material culture to be “regarded as a kind of text, a silent form of writing and discourse” (one of the key tenets of post-processual archaeology), but also emphasized that material culture is always a *social production*, not merely an adaptive mechanism or function. In other words, material culture was seen as “active” in the reproduction of social relations. While the textual/linguistic analogy facilitated a more nuanced consideration of the social production (and context) of material culture, conceptualization of technology as embodied practice remained relatively absent in early post-processual writings.

Conversely, French researchers of ethnology and prehistory had already situated material culture and technology within the realm of the “social body.” Drawing upon the earlier sociological and anthropological concepts of Emile Durkheim (the thing as a “social fact”) and, in particular, Marcel Mauss's “*techniques du corps*” (1935), the ethnologist/prehistorian André Leroi-Gourhan (1911–86) placed technology in the context of bodily gesture and knowledge. Mauss's “*techniques du corps*” recognized that technologies were embodied “social facts” (after Durkheim), shaped and influenced by social traditions (Mauss presciently described this relationship as “*habitus*”). Leroi-Gourhan developed this approach to tools and techniques in two books published in the early–mid 1940s, *L'Homme et la Matière* and *Milieu et Techniques*, but his major contribution to archaeological technology studies came twenty years later with the structuralist-influenced two-volume *Le Geste et la Parole. Technique et Langage* (1964), and *Le Geste et la Parole. II. La Mémoire et les Rythmes* (1965). In these works he detailed the proposition that “the tool really only exists with the gesture which renders it technically efficient” (1965, 35). That is, the artifact is animated by the gesture, a conception that formed the basis for Leroi-Gourhan's key contribution to technology studies, the *chaîne opératoire*—the sequence of embodied technical practices which transforms raw material into an artifact.

Leroi-Gourhan's work on techniques and technologies was, and continues to be, hugely influential in archaeological technology studies, particularly in the French-speaking academy. His 1940s–1960s technology research was mainly in the field of ethnology, but it was soon embraced by French anthropologists and archaeological prehistorians in the late 1970s, so much so that it seems reasonable to talk of a “French school” of prehistoric technology. Aside from his well-known structuralist analysis of European Upper Paleolithic cave paintings, his work on technology made little impact on English-speaking archaeology until the early 1990s, when an issue of the graduate student-edited journal *Archaeological Review from Cambridge* entitled “Technology in the Humanities” (Schlanger and Sinclair 1990) published in English a number of articles by key

authors in French ethnological and anthropological/archaeological technology studies—Robert Creswell, Pierre Lemonnier, Jacques Pelegrin, Nicole Pigeot, and Valentine Roux, as well as critical reflections on the work of Leroi-Gourhan himself. There followed the first English translation of *Le Geste et la Parole*, appearing as *Gesture and Speech* in 1993 (translated by Anna Berger).

With the *chaîne opératoire* now seen by some researchers as an analytical tool “as basic in prehistoric technology as elemental analysis is in chemistry” (Auduze 1999, 167), archaeological technology studies moved to a new prominence in various aspects of archaeological theory in the 1990s and early 2000s. Notably, Joan Gero brought archaeology’s relatively recent concern with gender to bear on questions about the long-assumed dominant role of men in the production of stone tools in prehistoric contexts. In her 1991 article “Genderlithics,” Gero drew attention to the hitherto unacknowledged role of women in such technological practices. Taking this critique further, and engaging current archaeological approaches to social agency and practice theory, Marcia-Anne Dobres (2000) noted the shortcomings of the *chaîne opératoire* approach when it came to the discussion of embodied and gendered agency. Although the concept refers to the relationship between materials and body practices, the latter were only formulated in terms of gestures and actions. Mid-1990s cognitive archaeological approaches drew attention to the cognitive knowledge and decisions that informed/structured such gestures and actions, as discussed earlier by Leroi-Gourhan, but fell short of conceptualizing the human body as the basic frame of reference in technological acts. Dobres, and others, further developed this general theory on technology—the relationship between techniques as the gestures and movements involved in artifact production and use, and the cognitive decisions, perceptions, and knowledge drawn upon and brought to bear on the execution of those techniques—but now situated it within a framework where the gendered body and embodiment were the central sites of technological practice. This perspective—the socialized, corporeal, and mindful body as the very essence of technological practice—aligned well with several post-structuralist archaeological approaches, sharing influences from key works

by Heidegger (*The Question Concerning Technology* (1982) and “being-in-the-world”), Foucault (“the political technologies of the body”), and Merleau-Ponty (technology as a “primary experience” of the body), among others. Postcolonial archaeologies are also now paying attention to nonwestern perceptions of matter, materials, and technologies, and to the political implications of challenging dominant western interpretations of such phenomena (e.g., Kusimba 2009).

In much current archaeological thinking, past technologies are often implicitly conflated with “material culture” in discussions of materiality and object ontologies. The influence of the *chaîne opératoire* still can be seen (although rarely cited) in notions of “object biographies” (e.g., Gosden and Marshall 1999) and the “life histories” of artifacts, approaches that take as a primary influence the sociocultural anthropological work of Appadurai, Kopytoff, and others on the historical networks of relationships between people and things, to demonstrate how the social biographies of objects are intimately entwined with those of the people who make, use, and exchange those objects. But some would argue that consideration of “social technologies” goes far beyond “things”—even “things” as conceptualized by recent post-humanist and new materialist perspectives. In the western industrial context, at any rate, technologies of the body and embodiment now range from cosmetic surgery, gender identity “realignment,” and intervention in the reproductive cycles of humans and nonhumans alike, questioning western biological definitions of humanity and the relationships between the human and the nonhuman. Perceived boundaries between the body, the self, and genders, synthetic and organic, are being subjected to radical, intimate enquiry by social technologies, and as students of such technologies, past and contemporary, archaeologists face new conceptual challenges in the definition of their object of enquiry.

SEE ALSO: Bodies and Embodiment; Experiment in Archaeology; Knowledge and Inference; Marine Molluscs; Mind and Cognition; Philosophy of Science

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Archaeology and the Present

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Archaeology in contemporary society and popular culture

Archaeologists in contemporary society are first and foremost known to conduct scientific excavations, and archaeology's widespread emblems are the spade and the trowel. But archaeology's continuing existence and general popularity does not only derive from its widespread scientific reputation and is at least as much due to the inspiring and sometimes inciting stories, popular entertainment, and fitting metaphors it provides in everyday society—going far beyond the realities of professional archaeology.

The appeal of archaeology in contemporary popular culture has long been derived to a large extent from prominent archaeological tropes such as the adventure of fieldwork, the discovery of treasure underground, the aura of the genuine thing, the detective-style analysis of the evidence, the revelation of insights and truths about the past, and the care given to the fragile archaeological heritage in the present (see *ARCHAEOLOGICAL FIELDWORK*). These tropes can also be applied to many other situations and contexts, and when this occurs, archaeology can acquire metaphorical significance. Authors such as Agatha Christie, Seamus Heaney, and August Strindberg; artists like Richard Long, Anne and Patrick Poirier, and Mark Dion; and a range of academics including Sigmund Freud, Walter Benjamin, and Michel Foucault have all drawn on archaeological tropes without actually being interested in literally working as archaeologists. Archaeology as a theme also occurs prominently in the visual arts, science fiction literature, adventure movies, games,

themed environments, and a large variety of other cultural genres and formats. Often archaeology becomes significant in all these contexts through its association with what lies below the surface, excavation, stratigraphy, traces of the past, treasure, analysis of material culture, and the act of remembering (Holtorf 2005). Archaeology can entertain and engage, provoke and disturb its audiences (see *PUBLIC ARCHAEOLOGY*).

Archaeologists who mention their profession to others are sometimes met with incredulity and the revelation that the conversation partner, as a child, also had entertained the dream of becoming an archaeologist—finding treasure and reconstructing the past—but that life had subsequently taken other turns. Scientific archaeology is however accessible to lay people not only by consuming popular culture but also by taking part in schemes through which they can participate in archaeological fieldwork. The demand of archaeological stories and experiences in contemporary society is, however, not only met by professional archaeologists but mostly through products and services offered by designers, film directors, tourist managers, public relations specialists, journalists, and many others. In all these ways, archaeology can not only directly enhance the quality of peoples' lives but also provide for the living of professionals who have no formal links to the academic discipline.

A variety of increasingly sophisticated scientific practices and approaches allow archaeologists to translate the particular material remains and topics they study into a rich array of stories that are about the past and/or about archaeology itself. Archaeological stories often engage with the big questions of what it means to be human; what human life was like in other periods; who we are, where we are coming from, and where we are heading as members of particular cultural groups; and not least how archaeological investigations reach their scientific outcomes (Holtorf 2010). Such archaeological stories often derive their currency from drawing on the opposition of us and them, self and other. Whereas some stories project present-day conditions onto the past so that we invariably recognize ourselves

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in other periods, others paint a picture of very different and strange worlds that constitute predecessors or alternatives to present-day conditions. Either way, stories about the past easily acquire political and ideological significance in present societies when they can encourage and legitimize or discourage and delegitimize certain political goals and ideological truths.

Therefore, it is unsurprising that the history of archaeology illustrates that archaeology is anything but an innocent pastime. Prominent episodes of political contestation in the history of the discipline include the debate about human evolution and primitive human ancestors in establishing the modern scientific worldview; the national celebration of prehistoric ancestors linked to an aggressive politics of identity in emerging and developing European nation states, most prominently the racial policies and territorial claims of the National Socialist regime in Germany 1933-45 (see *HERITAGE AND NATIONALISM*); the significance of dialectically evolving prehistoric and historic societies in Marx and Engels's historical materialism at the heart of twentieth-century socialist ideologies; and claims to the remains of their ancestors by numerous indigenous groups asserting their rights in the postcolonial contemporary world.

Contemporary archaeology: Understanding the material world in present society

Archaeology's methods and approaches can also be used to learn about contemporary society itself. The material world offers knowledge and insights into human conditions irrespective of time and place (see *MATERIAL CULTURE AND SUBSTANCES AND MATERIALS*). By approaching the recent past and the present from an archaeological perspective it is possible to gain an understanding of the contemporary world that differs from the ones available through other disciplines.

The chronological scope of contemporary archaeology is a matter of definition. An important characteristic of the field that also provides temporal guidance is that it deals with a past still within the experience and memory of the living. This gives the field a floating time frame

that moves forward as time goes by. In practice, contemporary archaeology deals with the last 100 years with a special emphasis on the period from World War II to the present. This being said, contemporary archaeology should not be considered as just another period subdiscipline; it is rather an investigation into the material world, its influence on our lives, and the way it shapes our understanding of the past, the present, and the future.

Dealing with an era from which there are people with memories of their own brings about not only particular methodological possibilities but also prompts special ethical considerations for the archaeologist (see *MEMORY*). One obvious methodological advantage is that it is possible to consult people and to include their statements in the analysis. These are valuable pieces of information that facilitate a deeper understanding of the historical period concerned, but they also bring into focus the fact that memory is a complex phenomenon indeed. Individual memories are remnants of personally colored experiences from the past that unavoidably—to a larger or lesser degree—have been revised due to later events and processes. As a consequence, memories do not always accurately reflect what actually happened. Memories that are not in agreement with historical facts are however of interest nevertheless; the discrepancies make us consider why the past is remembered the way it is and people's memories thereby inject a truly human dimension into an archaeological investigation. While the contrast between recollections and the material evidence is of interest to the archaeologist it may disappoint and embarrass the informant who feels that he or she has been "proven wrong." It is therefore necessary to carefully consider how to deal with people's memories in an ethically responsible way.

Archaeological sources can be used both to complement and to contrast other kinds of sources from the recent past and present. This complementary function applies especially to aspects of the everyday life of common people or with people living at the margins of society. Archaeology can shed light on how large-scale processes and important historical events were played out, and what material impressions they made, in relation to all people in society.

Archaeological sources may also contradict other kinds of sources. A well-known example is how garbage may tell a radically different story about peoples' consumption than is reported in interviews and questionnaires (Rathje and Cullen 2001). It shows that people sometimes are truly unaware of their actual life and behavior as consumers. Another example of contradictory sources is the official Soviet claim that all fallen soldiers from World War II had been buried which has been falsified by a voluntary search movement. Using archaeological methods, members of this initiative have so far found remains of more than 450,000 soldiers left in the field (Dahlin 2012).

Besides being important as a complement and a contrast to other kinds of sources, material remains are also valuable for evoking new interest in contemporary society in aspects of the recent past and present. Things have a suggestive power to attract attention and arouse curiosity; this is especially true of objects found on excavations. The encounter with an archaeological object may start a process where memories suddenly and unexpectedly are recalled, and new questions are posed. In order to find answers it may be necessary to turn to other sources, but if it were not for the objects evoking an interest, the questions would not have been asked in the first place (Burström 2009).

Alternative research aims—beyond getting knowledge about the past

Contemporary archaeology produces other stories about the recent past and the present than those that dominate history, and also raises fundamental issues concerning humans' relation to the world around them. These issues concern both what people do with things and what things do with us. Material objects have the power not only to evoke people's memories but also to trigger thoughts and emotions of various kinds. This applies in particular to things that people recognize from their own lives and which now somehow have turned into archaeological objects.

One kind of object that attracts a lot of interest from contemporary archaeologists as well as from the general public are modern ruins, e.g., derelict

industrial sites. What seems to fascinate people is the fact that something so relatively recent is already decaying and being reclaimed by nature. In this state the material remains of modernity join other relics of the past, and suddenly the traces of the recent past seem strangely timeless. In many cases they might just as well belong to an ancient society. This insight raises the question of whether chronologically structured history is the most suitable way to investigate our relation to this composite anteriority. Things separated by time may be closely connected through other qualities and through the sensual impact they make on people. The archaeology of the recent past and the present makes us realize that the contemporary world is a mixture of material and ideas from a multitude of different periods of time; an insight that is relevant to all periods of human history (Olivier 2011).

The thoughts brought to mind by modern ruins are not restricted to the past. Experiencing how time has left its mark on the material world reminds us of the limited duration of our own existence. It generates reflections about eternal human concerns such as the passing of time, continuity and mutability, life and death (see *TIME AND TEMPORALITY*). There are, of course, no absolute or definite answers to such considerations, but that does not mean that they are futile. They are clearly an important reason why people take an interest and care about the material residues of the past.

The emotional and existential dimensions of material remains have by tradition fallen outside the field of scientific archaeology as conventionally defined. Issues concerning how things from the past in a deeper sense touch us who are alive today have been considered too personal or too subjective to be approached scientifically (see *ARCHAEOLOGICAL SCIENCES*). This means, however, to deprive archaeological remains of one of their most significant qualities, that is, their power to move people (Burström 2009). The fact that the specific content of the emotions evoked and the reflections generated will vary between different individuals is no reason to exclude these dimensions from archaeological study. On the contrary, this variability forms an important part of the answer to the question of what things do with us. Studying recent periods where living people can be observed and asked,

facilitates this kind of investigation. The insights brought about are, however, relevant to all of archaeology.

Applied archaeology

When conducted in collaboration with partners in society, archaeology has the potential to transform society. Applied archaeology actively explores and develops uses of archaeology to help solve problems for the benefit of present society (see ASSESSMENT: HERITAGE IMPACT (HIA) and HERITAGE AND SOCIETY). Jeremy Sabloff (2008, 17) discussed this approach in terms of “action archaeology” which he defined as the “involvement or engagement with the problems facing the modern world through archaeology.”

Although some archaeologists have attempted to construe general laws of human behavior or social evolution that could inform future decision-making, the results reached thus far have not been convincing. But other archaeological knowledge has various practical applications in the present (Downum and Price 1999). Among others, studies of ancient irrigation systems inspired agricultural techniques in the present, empirically observed patterns of contemporary waste disposal informed innovative waste management, and long-term paleoenvironmental studies contribute to predicting environmental trends in the future more reliably.

The usefulness of archaeology does, however, not exclusively lie in the accuracy of the insights it provides about the past. Other uses of archaeology draw on its potential, for example, to develop communities and their regions, stimulate long-term historical thinking, engage patients in therapeutic practices, inspire many different audiences, and occasionally promote particular morals. In the future, archaeology may increasingly be applied to promote democratization, empowerment, and integration (Nakamura 2012) or to stimulate existential reflections across generations and communities. All such applications transcend the traditional scope of archaeology and are not commonly taught to students in archaeology (see AUTHORIZED HERITAGE DISCOURSE).

The potential new benefits to society are large and justify preparing the next generation of

archaeologists to explore this potential further (Sabloff 2008). Future archaeologists, therefore, will need to be able not only to relate their own professional expertise to larger societal challenges but also, and in particular, to understand the necessity to collaborate in joint projects with professionals in other disciplines, especially among the social sciences, to address these challenges critically.

Conclusion

Archaeology is not only the disinterested study of the human past and its remains but also a way of making a positive impact on present society in a number of other ways. As we have suggested, archaeology tells a variety of powerful stories about past and present and offers suggestive metaphors to contemporary society, archaeological methods and approaches can be applied to learn more about contemporary society and to trigger in people existential thoughts and emotions, and archaeological expertise can be applied to help solve challenges in contemporary society. It is important for future generations of archaeologists to be aware of these dimensions and to explore and apply them critically in professional practice.

SEE ALSO: Archaeology

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Assemblage

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Assemblages offer archaeologists new ways of conceptualizing the past for everything, from the materials they encounter to the communities they study. Rather than treating objects, people, or sites as bounded entities, thinking about assemblages requires archaeologists to focus on how these things emerge from the relationships that constitute them and how this emergent reality allows them to operate in the world. It is perhaps the most prominent new materialist (see NEW MATERIALISMS) idea at play in archaeology today.

Archaeologists are of course very familiar with the term *assemblage*, generally applying it to a set of artifacts, from a site or a region—an assemblage of flints or pottery shards, for example. The term, as it is defined in assemblage theory, is related to this, in that it refers to a gathering of different elements, but goes far beyond its traditional meaning to challenge how we conceptualize the world around us in both the past and the present. Archaeological examples will be set out below, but let us start with a familiar, everyday example. Consider your local library. We can treat it as an assemblage by thinking about how it is made up of all sorts of different elements: the books, of course, and the shelves on which they sit, but also the coffee shop on the ground floor, the staff who work there, the scholars who study there, and so on. Assemblages, however, are more than just the physical materials that constitute them; they include the rules and laws that operate there, in this case the fact you have to borrow the books rather than buy them, the signs that tell you to be silent, and the behaviors that ensue. “The library” then emerges out of all the relationships that exist between these different elements. Assemblages also have emergent properties. This means both that they are more than the sum of their parts (if you take away a single book, the building is still a library) and that they can act as a collective,

as when “the library” wants to recall your book. Equally importantly, assemblages are not static. Think of the way in which books are added to the library or leave it, staff members join or quit, students register or graduate, walls are repainted, and so on. Assemblages are thus always caught up in a process of what philosophers call *becoming*. Finally, assemblages are also multiscalar. Each of the books in the library is in itself an assemblage, one which emerges through the relationships between paper, ink, publishing companies, the thoughts and ideas of the author, and, from time to time, the interpretations of the reader as well. Even the library is one part of a larger assemblage such as a university, where it plays its role as one of the components of a wider collective.

The original idea of assemblage in this sense comes from the work of Gilles Deleuze and Félix Guattari and what they termed an *agencement*, which translates as “arrangement” or “assemblage.” Deleuze and Guattari (2004) used this idea as part of their much wider rethinking of philosophy, away from binary dualisms and static notions of being and identity toward more heterogeneous and multiple ideas of becoming. The concept of assemblage then gained popularity through the work of thinkers like Jane Bennett and Manuel DeLanda, both of whom are now widely read and cited by archaeologists. Bennett draws in the concept of assemblage to think about modern contexts. For example she examines how an electricity blackout in the United States in 2003 was caused by a whole range of interlinked factors, including “coal, sweat, electromagnetic fields, computer programs, electron streams, profit motives, heat, lifestyles, nuclear power, plastic, fantasies of mastery, static, legislation, water, economic theory, wire and wood” (Bennett 2010, 25). Tracing the reasons for the blackout, she finds that it emerged not simply from something like “mechanical failure” or “human error,” but from an ensemble of factors ranging from the economic processes that led power plants to be understaffed through a brush fire in Ohio to increased consumer demand, to the flow of electrons, and to the deficit of reactive over active power. This

event, which affected a huge swathe of a country and thousands of people, cannot be understood unless we look at the whole assemblage.

DeLanda's (2002; 2006) ideas are perhaps even more critical. Drawing on a long engagement with the work of Deleuze, DeLanda has examined how we can use assemblages to rethink geological processes, climate, science, and long-term histories. This points to a critical element of assemblages: they embrace both the side of archaeology we have traditionally thought of as humanistic (beliefs, meaning, identity) and more scientific approaches, which attend to the material elements of the world. In an assemblage there is no hard-and-fast distinction between these two, because assemblages are based on what DeLanda (2002) calls a "flat ontology." Most archaeology, whether from a processual or postprocessual perspective, has operated within a dualist ontology where cultural and social elements are treated as opposed to and different from nature and the environment. Different sides of this dualism have been privileged by different theoretical schools, but the division has remained in place. In contrast, assemblage theory argues that we need to start from a level playing field; there may be variation in scale, but that does not mean that certain things operate under one set of rules and other things under another. This also means that assemblage theory is nonanthropocentric, in other words is not centered around human beings. Instead people, who are themselves assemblages, take their place as one element among many others. So Bennett's analysis of the blackout does not privilege the role that human beings play any more than our library example above stressed the role of librarians and borrowers over that of books and shelves. These elements have made the concept of assemblages attractive across a range of disciplines, from anthropology and philosophy to politics and geography.

Assemblages, both in their original Deleuzian form and in the version developed by Bennett and DeLanda, celebrate what Bennett (2010) calls the "vibrancy" of matter, or what Deleuze and Guattari (2004, 454) call "a life proper to matter." Rather than treating the material stuff of the world as stable and static, these approaches examine instead how matter can be thought of as "alive" in one sense. This draws both on scientific concepts of how matter, despite its seemingly

solidity, is constantly vibrating and on the awareness that anything material will slowly erode away over time. Similarly, DeLanda urges us to draw on assemblages so as to think about what he calls the morphogenetic capacities of matter—that is, the way matter has its own processes, tendencies, and modes of acting in the world, rather than being at the mercy of human beings. Clay responds to certain kinds of engagement, stone to others. Thus, when we think about design, we have to think about how materials bring their own properties to the table and how specific kinds of relations between people and things can draw out new capacities without either person or material being the primary author.

Currently the concept of assemblage is being deployed in a series of different ways by archaeologists, its applicability at multiple scales meaning that it can be used to engage with a variety of archaeological questions. For example, Chantal Conneller (2011) has examined how we can offer a challenge to traditional questions of the *chaîne opératoire*—the sequence of actions that are understood as producing artifacts—by looking instead at the complex relations inherent in assemblages. Rather than following a series of "human" decisions about what to do in order to produce a particular form of artifact, Conneller traces the way in which people and the particular affordances offered by materials interacted to produce specific objects in the Upper Palaeolithic and Mesolithic of Europe. She shows how sometimes these affordances were located within the properties of the materials and sometimes in the relationships the materials had with other elements of the world, including the animals they were on occasions derived from. In a very different context, John L. Creese (2013) has described Iroquoian villages as emerging from assemblages that bound together people, houses, and forms of ritual practice in new ways. In a similar fashion, the present author has argued that whole communities of the past can be reimagined if we move away from seeing them as simply human gatherings (Harris 2014). If we think of them instead as assemblages of people, places, animals, materials, and even landscapes, then very different understandings of how these communities were formed and sustained can be developed. Finally it is worth identifying perhaps the most ambitious ways in which assemblage theory is being employed. Both

Gavin Lucas (2012) and Chris Fowler (2013) have used ideas rooted in assemblage theory to try and rethink the very nature of archaeological practice and archaeological research. Lucas, for example, argues that thinking of the material that archaeologists recover as the residue of older assemblages allows us to better understand the nature of archaeological practice, especially when we combine this thinking with an understanding of how this practice constructs new assemblages in the form of an archive. In parallel to this, Fowler examines how archaeologists themselves become incorporated in the ongoing assemblages of past artifacts and how archaeological work allows these materials in turn to be gathered into our narratives of the past in the present. For all these authors, archaeological science is one of the means by which we can attend to past assemblages and access the history of the relationships from which they emerged.

Archaeologists are therefore pursuing assemblage theory in a number of directions, from the interpretation of specific past contexts to embracing what it is that archaeologists and archaeological scientists do in the present. This research is in its early days, however, and a number of developing lines of enquiry can be imagined. What difference might assemblages make to our methodologies? How can its emphasis on a flat ontology be connected to how we practice archaeological science? How might we approach the relations between different material elements at a specific site and use visualization technologies to reconstruct assemblages in new ways? How can we use the multiscalar nature of assemblage theory to explore particular periods

in detail, working from the smallest scale of specific artifacts and contexts to the largest scales of entire periods and millennia? Many of these questions are being pursued in ongoing research projects, and more will surely follow.

SEE ALSO: Material Agency; Material Entanglement; Symmetrical Archaeology

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Behavioral Archaeology

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The centrality of “things” in everyday human life is widely recognized in archaeology, anthropology, and other disciplines. Modern material culture studies (see *ARCHAEOLOGY AND THE PRESENT*), the sociology, history, and archaeologies of technology (see *ARCHAEOLOGIES OF TECHNOLOGY*), and concepts such as materiality (see *MATERIAL AGENCY*), entanglement (see *MATERIAL ENTANGLEMENT*), and the new materialism (see *NEW MATERIALISMS*) are only a few examples. The diversity of methodological and theoretical perspectives related to the study of artifacts is robust and encouraging. For over 40 years, behavioral archaeology has approached social and behavioral science with a focus on artifacts, recognizing the importance of things in every aspect of human life (Schiffer and Hollenback 2010; Skibo and Schiffer 2008). Its practitioners have long argued that with its focus on material culture (see *MATERIAL CULTURE*), archaeology should be at the forefront of fields studying behavioral and technological change.

Following a theoretical outgrowth of the New Archaeology of the 1960s and increased concern with archaeological metaphysics and the philosophy of science, behavioral archaeology arose out of a need for a systematic, explicit, empirical framework to strengthen knowledge and inferences (see *KNOWLEDGE AND INFERENCE*) in the reconstruction and interpretation (see *INTERPRETATION*) of past human behavior. The approach was developed by William L. Rathje, J. Jefferson Reid, and Michael Brian Schiffer (Schiffer 1995, 1–24) at the University of Arizona in the 1970s and continued in the work of their students and others (Skibo, Walker, and Nielsen 1995; Walker and Skibo 2015). Currently, there is no uniform approach in behavioral archaeology. Instead, its practitioners are linked by a

reliance on the shared use of related methods, concepts, and theories in the study of socio-cultural phenomena. Unlike other conceptual paradigms, behavioral archaeology views human behavior as human–object interactions, privileging an artifact-oriented epistemology of the world to examine behavioral patterns, continuities, and changes in all times and all places. The framework is unique in that it defines archaeology more broadly than traditional views and is quite rigorous in its approach. It is a social science with “four strategies” that takes as its subject matter the interactions of people and things in the past *and* in the present (Schiffer 1995, 67–73; Skibo et al. 1995, 15–21). These strategies capture the diverse array of topics behavioral archaeology has focused on since the 1970s. Earlier studies focused on archaeological inference and evidence, formation processes, and the development of experimental laws through experiment and ethnoarchaeology. More recent research has turned to social questions of technological change (Schiffer 2011), communication (Schiffer and Miller 1999), ritual, landscapes, social performance, and power (Schiffer and Hollenback 2010; Skibo et al. 1995; Walker and Skibo 2015).

		Material culture	
		Past	Present
Human behavior	Past	1	2
	Present	3	4

Strategy 1 encompasses the traditional practices of prehistoric and historical archaeology, as well as studies in the history of technology. Its goal is a more rigorous interpretation of archaeological data with the important recognition of a difference between the archaeological record (see *ARCHAEOLOGICAL RECORD*; archaeological context) that we engage with and study in the present to make inferences about and reconstruct past living social systems (systemic context; Schiffer 1995, 25–34; Schiffer and Hollenback 2010, 22–25). Archaeological phenomena (i.e., artifacts, features, sites, and anthropogenic sediments) are outputs from active cultural systems, but subject

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(see DISASTER ARCHAEOLOGY; Walker and Skibo 2015, 205–219).

Strategy 4 also can result in applied outcomes. It studies current human–artifact interactions to understand larger patterns of contemporary human behavior. Others would recognize this strategy as modern material culture studies or archaeology and the present. The earliest behavioral studies of this sort began in the 1970s as William Rathje’s Garbage Project (Rathje and Murphy 2001; Skibo et al. 1995, 36–43). This program studied waste disposal behaviors, as well as formation processes in landfills, to debunk myths about “trash.” Its findings are valuable for waste management and recycling policy. More recent modern behavioral research examines phenomena such as art (Walker and Skibo, 97–110) and significant sociopolitical features such as the United States–Mexico border wall (Walker and Skibo 2015, 187–204).

Currently, modern behavioral archaeology has embraced a wide variety of research. This body varies in the types of questions and research goals adopted, but is unified by concepts and approaches arising from the four strategies. In addition, it is important to recognize that many approaches to archaeology today, which are not explicitly behavioral, utilize these concepts. For example, there is now a universal recognition of the importance of formation processes in constructing inferences about the past. Future behavioral research will likely continue to build on models of strong archaeological inference, but will embrace more applied endeavors, such as those illustrated in strategies 3 and 4.

SEE ALSO: Archaeological Record; Interpretation

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Bodies and Embodiment

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Introduction

Theories of the body and theories of embodiment (see EMBODIMENT) describe a series of perspectives that explore how humans perceive and experience the world through their physical and social bodies. Embodiment is distinct from concepts of “the body,” in that the former is a solely biological/material entity, while “embodiment” is a theoretical and methodological framework which acknowledges the socially constructed nature of the body and the ways in which it interacts with the world. The concept of embodiment is based on two fundamental principles: first, rejection that cognition (the mind) exists independently of the body (as posited by classical philosophers such as Plato and given preeminence during “the Enlightenment”); and second, rejection of the assumption that the biological, physical, and bounded body exists as the foundation for the interpretation of experience, separate from other aspects of the material and immaterial world (animals, plants, places, things). Arising from trends in sociology (Featherstone, Hepworth, and Turner 1991) and anthropology (Joyce 2005), in response to structuralist theories which divide the world into dualistic distinctions between, for example, mind and body, subject and object, perception and practice, theories of embodiment question our understandings of the concept of “the body” and seek to understand how physical and social bodies are constituted and reconstituted via interactions with other living and nonliving things.

Central to theories of embodiment is the acknowledgment that mind and body do not represent different facets of a person, and that ontological understandings of the world are constructed and mediated through the “practical ontology” of corporeal experience. In other

words, “while culture clearly bounds and directs individual understanding of cultural meaning, the actual process of meaning making and identity construction are built upon individual experiences, emotions, and interpretations” (Dornan-Fish 2012, 284). Robb and Harris (2013, 17) have captured this cocreative nature of body and world—this “dynamic feedback loop” (Dornan-Fish 2012, 285)—through their discussion of “body worlds.” Thus, theories of embodiment allow for conceptualization of the body as cultural and historical, biological and material, and acting as the medium through which individuals perceive, experience, and engage with the world, its objects, and places.

People, things, and places: archaeologies of embodiment

Phenomenological approaches in archaeology have sought to “people the past” and to understand past worlds from the human perspective, with a particular focus on the emotional and sensory aspects of places and things. It has become apparent, however, that we need to question what *kind* of people we were peopling the past with. Drawing on the *habitus* of practice theory, together with structuration theory, approaches to the body and theories of embodiment view particular ontological understandings of the world as historically and contextually specific: a “phenomenology of perception” (Csordas 1990, 33). As such, no one universal concept of corporeal experience can be assumed across time or space, including between people in the same society, or by the same person in different social contexts.

Bodies, identity, and power

If ontological understandings of the world are historically and contextually specific, then so are the many aspects that make up social identity. As such, social identities are relational, in that they are not predetermined but formulated in relation to those around us, and are, at the

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same time, mediated through the specificities of our physical bodies. Critics argue that too much focus on the subject-specific body risks neglecting overarching social power structures in which these bodies (these individuals) operate. Others argue, however, that individual choice and collective choice are not mutually exclusive categories. Indeed, Dornan-Fish (2012, 282) suggests that it is impossible to discuss concepts such as power without also acknowledging processes of internalization within our own bodies, since “it is in the process of individual meaning-making ... that shared cultural symbols gain or lose their power to constrain or enable social action”; that is, individuals are *parts* of social structures, not external to them. As such, theories of embodiment provide more nuanced understandings of the way in which power dynamics in society operate, in contrast to homogenizing terms such as “resistance,” which have the potential to misrepresent the intentions, experiences, and self-identification of both “oppressed” and “oppressor” (Dornan-Fish 2012, 291–2).

One of the first areas of archaeology in which theories of embodiment were explored were studies of gender and sexuality, particularly within feminist archaeology (see *GENDER AND SEXUALITY*), in which power and inequality are central themes. Butler (1993), a major influence on this theoretical turn, argued that terms such as “male” and “female” are not biologically absolute, but rather performed through a series of regulated practices. These practices in turn create idealized gender types and reinforce them as naturalized states of being. Take, for example, modern public lavatories and the strictly binary gender types that they reinforce, or studies that have shown the different ways in which people interact with “male” and “female” infants, engendering their corporeal experiences from an early age. Dissatisfied with assumptions that a stable biologically sexed body necessarily represents a uniform foundation for socially constructed gender, as portrayed, for example, through clothing and ornamentation, archaeologists have sought to understand the ways in which the corporeal experiences of different types of body created (and recreated) variously gendered ways of experiencing and understanding the world (and vice versa). In this dialectical relationship, these identities need not be static, since their

performative recreation leaves them inherently mutable and open to change. Such considerations do not limit themselves to gender, and include other facets of social identity such as age, class, and clan affiliation, which are simultaneously operating on and within the body, and in its representations (Joyce 2005). Before we can examine these aspects of a person’s social identity, however, we need to establish what we mean by “person.”

Embodiment and personhood

Within a liberal humanist framework, modern western societies place great emphasis on the individual and indivisible, bounded nature of the human body—a concept that has arisen from, and is supported by, our capitalist and consumerist economy. In this perspective, people are individuals and individuals are people. In our society, individual agency (the capacity to do things) is fundamental to concepts of freedom, empowerment, and moral responsibility, and, as such, there has been a rise to incorporate aspects of “the individual” and “individual agency” into past narratives.

The perspective of “the individual,” or indeed any universal concept of corporeal experience, should not, however, be taken for granted as an a priori state of being, and different “modes of personhood” are frequently recorded in non-western societies across the globe (cf. Fowler 2004) (see *PERSONHOOD AND OBJECTHOOD*). One mode of personhood often cited in contrast to modern, western ways of experiencing the world is “dividual personhood,” in which bodies are understood not as strictly bounded physical entities, but comprising a series of parts (material and immaterial), which can be separated out and exchanged (partible persons) or influenced and reconfigured by flows of substances (permeable persons) (Fowler 2004, 7–9). These different ways of experiencing the world can be found, for example, in Melanesia and India respectively, though shamans or members of any totemic society might also be considered to possess more fluid ways of understanding the construct of the physical human body. Even today, in some forms of Christianity, “possession” by evil spirits or being overcome by the power of God indicates

a perception of the body as permeable to other types of “person” and/or “flows” of energy (cf. Csordas 1990).

Indeed, drawing firm distinctions between “individual” and “dividual” persons represents something of a falsehood, since in most societies, a person’s understanding of themselves fluctuates between and within these two extremes, depending on context. Though the concept of “the individual” as a physically bounded body is often the dominant mode of personhood experienced in the modern West, there remain certain contexts in which dividual aspects of our personhood are elevated: in our attitudes towards the dead and our processing of grief, for example (cf. Crossland 2010). Objects associated with the dead—particularly those that have come into direct contact with the body (such as clothes)—are frequently treated as containing some lasting “essence” of that person, which makes their reuse or disposal particularly problematic. Furthermore, the language used to describe bereavement, such as people being “filled with grief,” suggests an underlying concept of the body as a vessel, through which our emotions “flow.” In addition, the modern western premise that individuality is something unique to humans is called into question when we consider the social status given to nonhuman agents such as pets. And what implications do concepts of embodiment and personhood have, for example, in our consideration of “post-humans” and other forms of artificial intelligence—can we, do we, and will we confer the status of “individual” to these bodies?

Embodiment and materiality

Archaeological studies of embodiment necessarily draw on theories of materiality, since it is predominantly through material remains (artifacts, for example) that we study the *people* of the past. Materiality describes the material and immaterial affordances (or bodily experiences) of an object, place, or thing; the hard, cold, and durable qualities of stone versus the soft, warm, and impermanent characteristics of wood, for example. We have discussed the central role that material and immaterial things play in structuring (and creating) our bodily experiences

and understandings of the world, and materiality plays a vital role in this. The materialities inherent in wood and stone have, for example, been variously employed as a metaphor for the human body (living and dead respectively), while bread and wine in the Christian Eucharist serve as metaphors for the body and blood of Christ (and also represent a modern, western example of dividual personhood).

In societies that tend towards dividual modes of personhood, aspects of a person’s body can be distributed in a range of material and immaterial things. As such, humans represent just one part of an assemblage or “entanglement” of plants, animals, objects, and places. Things and places that we may assume to be passive backdrops to human existence (landscapes and architecture, for example; see *INHABITED LANDSCAPES*) thus become active agents in the creation, negotiation, and maintenance of ontological understandings of the world.

Embodiment and agency

In an attempt to overcome modern divisions between subject and object, anthropologists developed “actor network theory” (see *ASSEMBLAGE*; *MATERIAL AGENCY*; and *MATERIAL ENTANGLEMENT*), which focused on the fluid relationship between humans and nonhumans. Others went further still, imagining humans and nonhumans as “entangled hybrids,” “socio-technical assemblages,” or “socio-technical collectivities,” in an attempt to move away from the mind–body dichotomy (Crossland 2010, 394). In these approaches, neither human nor object are afforded any particular “agency” over one another (*contra* Gell), as this is viewed as overly subject-centered and humanistic.

Here we see a theoretical tension between the call to consider the agency of objects—in acknowledgment of the central role our material surroundings play in the constitution of our embodied selves—and the effective loss of agency in entirely relational and symmetrically distributed concepts of this embodied self (cf. Crossland 2010, 394). Indeed, critics of actor network theory see it (in its most reduced form) as positioned in direct conflict with theories of embodiment, since it erases the performative

aspects inherent in the constitution of our bodies. In denying agency to people in the past (particularly those with more “dividual” modes of personhood), they are left unable to distinguish their minds and bodies reflexively from non-human things, other persons, or the societal structures that “bind” them, nor to pursue any goals independently of society at large (cf. Crossland 2010, 283; Dornan-Fish 2012, 284). Indeed, “intentionality” lies at the heart of theories of embodiment, and “all archaeological interpretation is to some extent about understanding past intentions” (Dornan-Fish 2012, 287). It is arguably the under-theorizing of the complex intentions and motives of embodied persons in the past that leads to oversimplified readings of the archaeological record, and we walk a “fine line between postmodern conceptualizations of society as nothing more than a jumble of unrelated subjects, and cultural constructivist conceptualizations of individuals as nothing more than a sum of their collection of identities” (Dornan-Fish 2012, 294). Diminishing the possibility for agency and intentionality has implications not only for the past but also for the future, effectively writing theories of embodiment out of discussions surrounding post-humans and artificial intelligence; discussions that are likely to become more central to our understandings of what it is to be “human,” as the distinction between “biological” and “technological” bodies becomes increasingly blurred.

Post-script: embodiment and the dead

Though they form the basis of our interpretations about the past, the dead (as dead people and as dead bodies, rather than as silos of information on the living) are often overlooked in discussions of embodied experience in archaeology, emphasizing our modern adherence to the mind-body dichotomy (cf. Crossland 2010, 402). It is possible, however, that death simply signaled (and continues to signal) a “transformation of embodiment” (Crossland 2010) rather than its cessation, and that our failure to ascribe embodiment to dead bodies reflects our modern philosophical positioning. Indeed, Crossland’s (2010, 402–405) discussion of forensic archaeology demonstrates that the language commonly used in relation to

dead bodies (particularly in mainstream media) demonstrates a tension between the dead as representing “matter without mind” (Crossland 2010, 402), and yet possessing continued agency. Considering embodiment in the past therefore prompts us to reflect on our own ontological positions (and contradictions), and the ways in which we “use” and interact with the dead (including the long dead) in contemporary society.

Archaeological bodies and embodied archaeologies

Theories of the body and of embodiment are relevant not only for how we understand people in the past, but also for how we understand ourselves and others today. Indeed, they are critical to our understanding of the underpinnings of archaeology as a discipline. Archaeologists have increasingly become aware of the andro- and ethnocentric biases inherent in interpretation. Theories of the body and of embodiment take this a step further, in their recognition of the historically and contextually situated embodied self. As such, they force us to acknowledge archaeology as a socially mediated form of constructed knowledge and practice, and what this might mean for our understandings of the past. They also force us to reevaluate the structural *status quo* of contemporary society, and highlight the role of the archaeologist in maintaining or challenging the embodied “norms” we take for granted. By helping us to step a little closer to those whose lives we glimpse through their relationships with the material traces of the past, we also create more nuanced understandings of our own place in the world.

SEE ALSO: Material Metaphor; Material Symbols; New Materialisms; Perception and Experience; Substances and Materials

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Creativity

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Humans have always been creative and everyone is creative. To imagine otherwise suggests that some people can do things, while others cannot. Archaeologists have not always been so generous in their accounts. For instance, humans have historically only been regarded as creative since c. 40,000 years ago, with the advent of a “creative explosion.” Such eruptions are often depicted as first occurring in what is now termed Europe (mostly in Spain, France, and Germany first), with the arrival of decorated caves, sculpture, ornamentation, and musical instruments. For example, we have the so-called *Lion Man* mammoth ivory sculpture, Germany, at c. 40,000 years ago, and the earliest black drawings and charcoal marks in Chauvet Cave, France, around 37,000 to 33,500 years ago (Jones and Cochrane 2018). We have evidence for some of these elements occurring in Africa around 75,000 years ago, at Blombos Cave. Here, numerous engraved red ochre pieces were discovered, and at least 49 perforated shell beads, with marking from use and the application of ochre. By 10,000 years ago, traditional narratives report that humans started to think symbolically, with the development of status, value, power, and metaphor. These are seen as complementing the rise of sedentism with domestication, soon followed by social stratification, inequality, cities, and metallurgy.

Renfrew (2008) creates the notion of a “sapient paradox” while thinking about the materials humans modify. Renfrew questions why humans from at least 150,000 years ago, who share the same potentialities as us (they are anatomically modern and sapient), do not create the kinds of decorative assemblages that we see around 40,000 years ago (Blombos being an exception to the rule). He further puzzles why it is only around 10,000 years ago that humans get their

act together in a creative fashion, and started to build the world (Renfrew 2008, 2043); that is the paradox. Improved climatic conditions from the late Ice Age onwards helped, but do not fully address this quandary. The short answer is that there is no paradox. Gamble and colleagues argue that archaeologists are stuck in a *what you see is what there was* approach to the past (2014, 152). Such perspectives only afford past humans attributes that can be inferred from the materials found (e.g., chipped stone and butchered animal bone). Gamble and colleagues (2014) suggest that we must consider elements that might not survive in the ground, but are still key to being human. These can include: friendship, laughter, emotions, dance, language, music, and of course creative thoughts. The challenge for the archaeological future is for such considerations to complement more material based approaches.

Another facet of traditional accounts relates to replication of technology as stasis. Early humans are depicted as lacking originality and change is the exception. Copying and repetition of form is, however, not mere replication via template; it is a complex and ongoing alignment of things in the world (Hallam and Ingold 2007). It takes work, and therefore even the maintenance of long-term traditions that are similar are not inertia, but are active creativity (e.g., Acheulean and Levallois techniques). Creativity is not *just* about change—there is no reason why the 100,000th version should be any less creative than the first—as all are momentary engagements with the world. There is also no guarantee that the 100,000th version will be like the first, while it is being worked with. Replication of existing forms leads to variations in the situated processes that might not be visible archaeologically (e.g., within a group of people). A legacy of the Renaissance is that the creative act is about discontinuity rather than an ongoing process. Historically, archaeology has been retrospective and primarily focused on the *created* (what was made); more recently it looks towards the *creating* (the process of making) (e.g., Jones and Cochrane 2018). Creativity is an ongoing journey of repetition and

repertoire building; definitions and approaches influence how we think about the past.

How we recognize creativity in archaeology today is framed by the development of the concept. It has had a long and deep history in the West, with origins in the Judeo-Christian traditions of Genesis. Medieval beliefs fostered the notion that God created things from nothing; humans merely juxtaposed existing things in new ways. In the thirteenth century, the term *create* was predominantly in the past tense (was created). By the fifteenth century, we witness the occurrence of the present principle *creating* (what is being created). The belief that things are made from nothing (i.e., they are original) persists. Human agency does not really become associated with acts of creation until the sixteenth and seventeenth centuries; it is, however, often seen as suspect when it does occur. From the eighteenth century onwards, many seem to be more confident in the human ability to create, and the word *creativity* first appears in English texts in the mid-nineteenth century. This is also when we have the late Romantic elevation of the artist as an individual genius, and beliefs in authenticity, as an anathema to mass reproduction. Through the twentieth century, creativity became something that anyone could claim (buy) or aspire to, via processes of democratic consumerism (see detailed discussions in Pope 2005; Hallam and Ingold 2007; Svašek 2016). A recurring theme running through this century was that to *copy* was not to *create*. Such thoughts have cast a long shadow over archaeological explanations.

Today, the idea of the Lone Creator (the genius, the talent) existing in the West is no longer dominant. Instead, creativity is viewed as existing within networks that foster a diversity of perspectives (the Internet has helped here). Creativity is no longer the result of the void, but rather an assembly of preexisting elements, often in different configurations (see also ASSEMBLAGE). Conversely, creativity is still linked to innovation and newness; creation from a void. Not all like the word *creativity*, some think it a lazy debasement that lowers all to a common denominator. Yet, we live in a world that wants more and more creativity (irrespective of its origins), and many are strongly encouraged to be creative in the workplace (Liep 2001, 5). One of the driving factors of creativity in contemporary commercial sectors is

leadership as mediator-based creativity; here the leader acts as moderator. This can work via four mechanisms: motivation, affect, cognition, and context. This can lead to an empowerment of the group and the forming of new creative relations. The early Neolithic stone known as Grand Menhir Brisé, Locmariaquer, France (c. 4,700 BC), wonderfully demonstrates such mediations. This megalith is currently broken into four pieces; when whole it was c. 20 m long and weighed over 300 tonnes. It was quarried from about 4 km away from its current location. The efforts involved in finding the material, removing it from the ground, shaping it, moving it vast distances across terrain, and finally erecting it (probably next to 18 other standing stones), were epic. This was only possible by collaboration and creative leadership; the ability to influence and affect others in the world (Richards 2013); the power of charisma. That it fell and smashed also highlights the risks involved in mediator-based creativity.

The twenty-first century has already witnessed provocative changes, in part generated by economic and political problems, and fueled in some instances by weak leadership (Shalley et al. 2015, 2). Within such environments, companies and industries that remain static (e.g., they do not create new things) are often seen as being in a state of dying. To resolve such issues, many companies name creativity as a priority and solution (Shalley et al. 2015). This makes sense, as huge dividends can be accumulated by the creative arts. The importance of a new idea is key to creativity (as idea generation) and innovation (as implementation). Again, these contemporary approaches to creativity influence how we depict the past. By acknowledging how we think today, we can move beyond progression and innovation as forms of social evolution, resulting in explosions and revolutions in deep history (Gamble et al. 2014). Creativity in archaeology is no longer just the prerogative of the divine or humans, it can also work with assemblages of things, that collaborate or disrupt (Olsen et al. 2012).

Archaeology can offer important deep time perspectives that are less available to other disciplines; we can examine change over long durations, and we are able to examine how creativity relates to a spectrum of factors. Some people are happy to take risks and violate paradigms; this mostly works best after one

has first learned the rules. Skilled practitioners often excel by being able to improvise and adapt to changing circumstances (Hallam and Ingold 2007, 12). An archaeological example of such processes can be seen in the decorated Neolithic macehead from the Knowth Site 1 passage tomb, Ireland. Recent applications of reflectance transformation imaging (RTI) on the flint macehead has helped reveal how it was worked (Jones and Díaz-Guardamino 2018). The macehead (790 mm long) is decorated with spirals, lozenges, and arcs. On each side of the macehead there is a single spiral; on one side there is an arc that inverts at the ends, and around the central handle-hole there are lines, one of which radiates off into a spiral. The ends of the macehead have close fitting lozenge motifs that are carved in relief; the spiral decorations on the front and sides of the macehead are executed in shallow relief. This is an unusual technique among the known corpus of decorated things from Neolithic Ireland and the United Kingdom. The white flint is much harder than the orange, and these texture differences affected the Neolithic carver. On one of the faces of the macehead, the spiral decoration passes through a region of hardened white flint, thereby deflecting the carver's hand, disrupting attempts at symmetry and perfection. The flint does not collaborate passively. Modern technology allows us to see new things, and it highlights that at any given moment, things can go astray. Creativity works via process, involves risks and some certainties, and is always in a historical moment.

Destruction is also a creative practice. For instance, the island of later Neolithic and early Bronze Age Crete is a world popularly characterized by athletic men, bare-chested women, and snake reverence. It has also produced some of the most iconic sculptures in the world, among them the so-called "Snake Goddess" figurines from the Palace of Knossos (c. 1900–1100 BC). Excavating in 1903, Sir Arthur Evans and his team, discovered two cists within the floor of the palace; within them (known as East Temple Repository and West Temple Repository) was found fragmented faience figurines. Here, we have not only deliberate breakage but also specified deposition. Two figurines present identical breakage patterns: they are both decapitated, have the left arm removed, and are broken below

the hips. They demonstrate fracture lines caused by impact from a heavy instrument or by being held in the hand and smashed into a harder surface. What we have is not only intentional mutilation, deposition, and assemblage, but also the deliberate separation of parts (see Jones and Cochrane 2018, and references within). Fragmentation might be a means by which relations between people and groups were maintained or established. Significances arrived via creative destructions and additive subtractions.

Things happen in the present. We now exist in a post-*Gathering Time* Bayesian world (see BAYESIAN STATISTICS). For years, approaches to understanding how creative things happen were hampered by ahistorical essentialist and universal narratives, that could be applied to any place at any time. Instead, Bayesian dating is now able to help us create useful models for witnessing the tempo of change in the past. Most recently it has been successfully worked through Upper Paleolithic decorated caves (see the newest set of dates above), Neolithic monuments, and Anglo-Saxon graves. Archaeologists are challenging the idea that things, particularly ones worked with by humans, were the result of predetermined ideas. Instead, in explanations we have relations of things—affected and affecting—determining overall process. Gone also is the established belief that things happened slowly over long periods of time in the deep past. The Neolithic monument named West Kennet Long Barrow, in England, highlights such shifts in perspective. For most of the twentieth century, it was explained to have a slow history, being open for some 1,000 years, with the bones that were deposited within, often being moved around the environment. The bones were old venerated ancestors and were associated with fertility; Bayesian modeling gave us a different narrative. We now have a relatively quick build monument created, with at least 36 people placed in it. This happened at a generational scale of 25 years or so, between 3,670 and 3,635 cal. BC, with the last primary deposit going in c. 3,640–3,610 cal. BC. We no longer have timeless or anonymous forebears; rather there are known, remembered, and accountable people. In terms of expression and creativity, this is a completely different story that operates in human lifetimes. High Resolution dating techniques (e.g., Bayesian modeling), strontium isotope analysis

(see MOBILITY AND STRONTIUM ISOTOPES), aDNA studies (see e.g., DNA: MITOCHONDRIAL) inter alia, are increasingly allowing us to notice specific changes and movements at different scales, for example, lifetime, generational, settlement, and environment. We can now better witness the actions we have previously speculated over as they unfold. Creative processes do work, on the ground, beyond theoretical modeling.

As we have seen, creativity is a difficult topic to pin down, because it is slippery. It is impossible to define as it has no single image of thought of its own. It subverts attempts to subordinate it to a particular model (Pope 2005, 36), via a paradoxical process of *defining creativity by creating definitions*. Ironically, archaeological writings themselves are often the greatest acts of creativity.

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FURTHER READINGS

Critical Theory

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Critical theory assumes two positions that are complementary and even essential to each other. One comes from the Marxist scholars who adapted economic and political analyses from Marx and Engels to late twentieth-century capitalism, particularly focusing on why many of the most exploited in a society could not see clearly the institutions that exploited them (Lukács 1971; Althusser 1971; Habermas 1984–7; Frisby 1996). Those people, classes, groups, and ethnicities often supported proxies for those who were ruining their economic lives. Such an emphasis—such a problem—often settled on studying ideology as an intellectual object. These scholars founded the Frankfurt School and critical theory.

A second and much less integrated assumption in critical theory is the notion of projection from psychoanalysis, as articulated by Freud (Žižek 2012). Some archaeological projects see the elements producing conflict in the present as being placed on the past, making the past unable to serve the present independently or scientifically, and making the past a function of those parts of society that are least able to see that capitalists satisfy their own interests (Orser 2004). The idea that the past was made to serve the interests of the currently powerful was established before Freud. It is only in the last 30 years that this idea moved into archaeology.

Critical theory produces two kinds of archaeological analyses. Most of these concentrate on economic and political factors, because that is what their authors (Orser 2004) think is most useful as they see the needs of their own society. Second, critical theorists also write archaeological presentations of groups, classes, populations, and regions whose past is a scandal to capitalism. While I use this word to catch attention, it actually has two meanings. Critical theorists make it their job to find and describe the exploited (Delle,

Mrozowski, and Paynter 2000; González-Ruibal 2008; Larkin and McGuire 2009). One device employed to do this is to describe the lives, customs, heroic attempts to escape exploitation, early deaths, and short lives of those people whom capitalism ruins in its quests for raw materials, markets, cheap labor, cheap transportation, noncompetitive conditions, unregulated business practices, and a supportive system for collecting wealth in unlimited ways and amounts. This is where critical historical archaeologists have made the greatest progress, reshaped the field and its goals, made the greatest impact in the classroom on undergraduate and graduate students, and faced the greatest difficulty with colleagues in cultural anthropology, who often prefer to see a more complex world, one less determined by economics and politics.

No one ever said that Freud and Marx set out to achieve the same thing. Only by saying that both created critical theory could anyone say that they had something in common. The element in common is dealing with living conditions now, today—which is often so difficult because there is so much exploitation on the one hand and so little understanding of where it comes from and what to do about it on the other (Žižek 2012). Freud, as we all know, dealt mostly with patients, not with society. But, no matter how much that point is stressed, we all know that the point of all public archaeology, almost universal now, is to provide an answer to the big question: Where do we come from? (Lukács 1971)? How did we come to be in the condition we find ourselves in now? Public archaeology, while frequently light on its delivery of answers to these panhuman questions, is an offshoot of Freud's understanding that the present projects itself onto the past to justify its actions and to hide its motives. Public archaeology can be used for tourist purposes, but usually is not. Its aim is to show how the past is composed, put together, made, or interpreted. We think up the past; we don't dig up the past. This was our final sentence on public excavations in Annapolis. This is the second kind of analysis produced by archaeologists writing with critical theory (Sayers 2015).

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Freud's work in the hands of critical archaeologists has as its purpose putting in anyone's hands an understanding that not only is his/her past accessible and available, but there is an entire scientific field devoted entirely to achieving this very end. There are professionals to talk to who know the evidence for slavery, indenture, factory working and living conditions, eating conditions, medical conditions, early death, diseases, prisons, workhouses, famines, massacres, and torture chambers. Critical archaeologists have done all these analyses and so much more. All this work is done to tell us how we got into the conditions we are in, who is responsible, and where the other history is. Just as Freud said, the facts are friendly, so critical archaeology presents a past that unifies people with a current need for answers to the question of where the past went and, once retrieved, what it can say that is freeing. Freud actually saw dreamwork as akin to archaeological stratigraphy. He knew he was using a metaphor. In critical archaeology we are not using a metaphor. We have seen that, when people explain out loud how they and theirs came to be in their current condition, using the language of the masters, people listen and accord respect. Does this make a difference (Žižek 2012)? Yes. As people who only guessed at a past come to see both the evidence of one and how to reason with the evidence, there is a different reality that is created. Does it stop exploitation? It does for some. Is it a redemptive act against capitalism? No. However, this way of thinking about, and doing, archaeology is new, if we judge by what American archaeology looked like before the 1960s.

It might be wise, at this moment of doubt as to whether critical archaeology has or even can accomplish anything, to place our collective scientific efforts within the objectives of the origins of nineteenth-century archaeology. We know, or at least are told, two origin stories about the reasons why prehistoric archaeology was founded. One, and a minor one at that, was to achieve a history for those nations and peoples not touched by Roman expansion into northern and western Europe. Digging in the ground was to be the alternative to not being mentioned by Julius Caesar, Hadrian, or Constantine. The second and far more important origin story was to provide an entire empirically based narrative about human and cultural origins beyond those

promoted by established churches, themselves viewed as too powerful, ignorant, or corrupt to be allowed to be the keepers of anybody's genesis.

With such a point, archaeology could and did use Nicholas Steno's insights into stratigraphy to eventually build a universal chronology free from supernatural intervention, underpinning a humanity that could be understood apart from employing sin, soul, purpose, or redemption. For better or worse. This secular yet noble purpose was to be rational and has succeeded in producing archaeologies for virtually all peoples and places on the planet.

A critical archaeology fits into this idea of a secular archaeology by being socially redemptive within the Marxist tradition. Its users ask: How can society, particularly capitalist society, be reformed (Althusser 1971; Lukács 1971)? Compared to nineteenth-century archaeology's concern with secular origins, a critical archaeology informed by Freud's work uses a more locally situated voice to discover what social or political matter needs to be worked on in such a way that archaeology or material culture can provide an answer. This usually means that archaeologists ask the people we or they work with what they want to know or achieve through archaeological work. This effort is often called public archaeology; it has taken many forms over the last 30 years and has had an impact that has been neither fully evaluated nor recognized.

The common link between the bigger early goal of archaeology and critical archaeology is a concern with the conditions of the world that archaeology moves in, on the understanding that it is this world that archaeology serves. How does archaeology fix conditions now with its work? Such a statement serves a local and a universal purpose simultaneously (McGuire and Paynter 1991; Larkin and McGuire 2009).

One example will make clear how critical archaeology works—but over decades. Historical archaeologists began work on North American plantations 40 years ago. We excavated slave quarters, overseers' cabins, great houses, fields, canals and dams, sugar mills, cemeteries of slaves, biracial communities, African American houses in towns and cities, property of people who were free before US Emancipation, African religious practices, Afro-Christian sites; and we talked with descendants, other communities, and anyone

in media who could reach any of these peoples. There was a search for African customs and traditions, or for some culture carried from Africa to North America. There was a concern with the archaeology of those who freed themselves from slavery, racism, segregation, tenancy, and halfway manumission. This was the archaeological version of the American Civil Rights movement. This effort in historical archaeology was not founded to be critical archaeology, even though some critical archaeologists worked within it and used critical theory to make their contributions.

The founders of the American Civil Rights movement certainly knew the neo-Marxist ideas of post-World War II Europe that, taken together, are critical theory, yet those ideas were barely visible in plantation archaeology; but they can be. In 1982, Orlando Patterson published *Slavery and Social Death* (see Patterson 1982). Patterson is a sociologist and quotes much of the same literature used by historical archaeologists who use critical theory. He might not call himself a critical theorist, but that does not matter given his main ideas, clearly so self-reflective on our own society that they complement critical theory and carry it further than we historical archaeologists do.

Patterson (2012) has three ideas that can revolutionize plantation archaeology and African American archaeology. One is that a slave—any slave in Greece, Rome, the Caribbean, or North America—is made into the property of the slaveholder by violence, as a person having no legal rights left, no ownership of her or his children or spouse, no property, possessions, or self. The enslaved has no former name, country, cultural tradition, kin, or history. Nothing remains. Through unpredictable and wonton violence, the slave must remake himself and herself into an image provided by the master, acknowledging the master's complete control over the enslaved's body, sexuality, life, and future. The slave is to become a parasite living on, off, and for the slaveholder. This is what Patterson calls social death. This is not an idea that has penetrated plantation archaeology.

Patterson's (2012) first point goes on. Because the enslaved's kin are owned by the slaveholder far into future generations and because slavery attempts to erase everything that marks a difference between a slave's former self and the slaveholder, the slave is left empty. When this

happens legally, over many generations, only a living corpse remains. The mark of former slavery is a combination of established inferiority, racist ideas of subordination, historical ignorance, but above all an attempt to create nothingness in a person. How to put humanity back into this emptiness has hardly even occurred to us as historical archaeologists, because we have not normally seen the depth of the problem. Yet that is supposed to be the role of plantation archaeology.

Patterson's second idea is that St. Paul invented, out of the teachings of Jesus of Nazareth and the Hebrew Bible, a version of Christianity that served Roman slave society by focusing on salvation through redemption from sin as well as on punishment for violating God's laws or commandments. Pauline Christianity preserved class, property, obedience, sin for disobedience, and stability within what was, at the time, the world's largest slave society. This became the religion of the slaveholding South for blacks and whites, as both groups experienced the emotional depth of the Second Great Awakening. There was to be no rebellion on either side. Patterson's novelty is not his critique of Christianity in St. Paul's hands. His novelty is bringing to life, in the American South, a religion created for slaveholding Rome, by offering a hypothesis that the Christianity of both places was the same and served the same purpose, whether believed in by slave or slaveholder. Here is St. Paul: "Slaves, obey your earthly masters with respect and fear, and with sincerity of heart ... Obey them not only to win their favor when their eye is on you, but as slaves of Christ ... And masters, treat your slaves in the same way. Do not threaten them ..." (Ephesians 6: 5–9). Where, we might ask at this point, is the archaeology of this hypothesis?

Patterson's (2012) third point has never occurred to those of us writing about African American archaeology: what slavery does to the slaveholder; yet the question has been known for years. The violence needed by the slaveholder to make an enslaved person is constant, unpredictable, given often for no reason, and has as its purpose the utter degradation of the slave. Marcus Aurelius knew this made a demon of the slaveholder. Frederick Douglass saw this result as well. We, within critical theory, missed it. How and with what result? We have left the slaveholder alone, or to the novels of William Falkner. We

have never had a good way of understanding the toll that inflicting and rationalizing violence took on a master's personality, on the slaveholding class, or on its Christianity.

Patterson's (2012) third point continues. He points out that social parasitism is supposed to make the slave a function of the master's complete self and of his desires. But the reverse happens. The slaveholder comes to be the parasite on the slave, who provides a sense of virility, importance, accomplishment, and wealth and a supplement to the slaveholder's being. So the master is as degraded as the enslaved has to be in order for the slave to be kept a slave. How do we use these critical insights?

We use them in two ways. For the purpose of using critical theory now in historical archaeology, I offer the hypothesis that slavery in the United States and in the West never went away. It remained and was transformed, and our job as historical archaeologists is to use its archaeological traces to understand its origins and to deal with its victims. Such an approach allows us to maintain a focus on the modern descendants of North American slavery as well as to concentrate on enslaved people who are not African Americans but who still live under conditions called trafficking in persons (TIP).

The concept that links legal slavery in North America, descendants of North American slavery, and trafficking in persons is manumission. Orlando Patterson offers the idea that Roman slaveholders saw that their greatest tool to control a slave was the slave's desire for freedom, independence, worth, and dignity, all to be achieved through manumission. Because manumission worked only insofar as it was a promise and a possibility, it could never be fully realized, but was always, even when achieved, conditional. Manumission, to work, could never be complete, otherwise the slave could not be controlled any longer. Manumission had to be partly real, partly lie. With the promise of manumission the slave could be seen to work very hard for it. But, even when manumission was achieved, the slave was still stigmatized by his/her former status. So slavery never fully went away. In North America this stigma was retained through Jim Crow racism and its laws.

It is this conceptualization of manumission that leads us to understand the need for

an American Civil Rights movement and our involvement in plantation or African American historical archaeology, the importance of many different Afro-Christian religions and churches, and the extraordinary resilience of racial inequality in North America. In this sense, because manumission was a half-promise, we can understand that the descendants of North American legal slavery do not want their unique history to be compared to slavery in ancient Greece and Rome, where slavery really is gone. With these arguments, historical archaeologists have a critical reason for not abandoning African American historical archaeology. The critical reason is: African American slavery never fully ended, but continued and continues through racist efforts to keep some citizens subordinate.

Once we have an intellectual way to see continuity in slavery over time, from Greece, Rome, the Caribbean, and North America, because the conditions and the definitions promoting it continue, we can see and add living slavery.

Such current slavery is called trafficking in human persons and is well documented by the US State Department (<https://www.state.gov/documents/organization/258876.pdf>); it, too, has recently been analyzed by Patterson (2012). The State Department report counts over 35 million slaves in the world today, most of them coming from the United States, Mexico, and the Philippines. The report counts 60,000 in the United States in 2016. The point here is that a critical approach asks about political and economic conditions in the past and how these allow us to see how peoples today came to be in the condition they find themselves in. Such an approach allows us to see that slavery is not dead, may never have been fully eliminated in nineteenth-century North America, and exists again as trafficking in persons.

For example, the 13th Amendment, though meant to emancipate, did not do away with slavery in our society. The amendment disallows involuntary servitude "except as a punishment for crime." Recognizing that the high incarceration rates in the United States are an aspect of a slave-permitting society is important to addressing that problem in its modern form. The race-based justification for slavery on the plantation did not end in the nineteenth century. Racial disparities in the criminal justice system

carry prejudices and inequities through to the present day. As critical historical archaeologists, we see the relevance of these issues to our purpose in conducting our research.

How to study all this? We end with Laura McAtackney, whose work in Northern Ireland covers the Maze Prison and the murals on the walls that divide Catholic and Protestant public housing sections of Belfast. She gives us the lead on how to study the archaeology of imprisonment and on the formation of demonic personalities.

A critical archaeology begins by defining a part of a modern society that does not work right, often because of a group's impoverishment. The "why" is the job of historical archaeology and leads to a locus in the past that we can call an archaeological site. The act of excavation is always one of explanation, through archaeology, to the exploited and to the exploiting, in the hope that the exploiting can eventually realize that, if they don't reform ...

SEE ALSO: History and Sociology of Science; Public Archaeology

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Empiricism

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Empiricism is the philosophical outlook believing that the origin of all knowledge is based on our sensory experience. As an epistemological view regarding the source, constituents, and limits of knowledge, empiricism dates back to antiquity, reverberated through the Middle Ages as the Aristotelian maxim “there is nothing in the intellect that was not first in the senses.” As such, empiricism can be regarded as a counterpoint to rationalism, the philosophical view made famous by Descartes in the early seventeenth century, which in stark contrast to empiricism maintains that reliable knowledge is achieved by rational contemplation alone.

During the seventeenth and eighteenth centuries, philosophical empiricism developed into empiricist forms of idealism and skepticism mainly through the works of early British empiricists Locke, Berkeley, and Hume. While their philosophies differed greatly, their common conviction that “there are no mental contents that cannot be derived from sensation or reflection” identifies all three as empiricists (Atherton 1999, viii). To this end, Locke, for example, held that knowledge is limited to the perception of ideas provided by our senses, and things external to sensation cannot be known. Berkeley adopted a more radical ontology. He argued that in order for anything to exist in the first place it had to be perceived by a sentient being. Perception, for Berkeley, is perception of sensations and ideas rather than of external material objects.

An important aspect in Hume’s philosophy regards the relationship between observation and expectation. Hume saw imagination rather than reason as the operation by which the mind generalizes from observations, and doubted the justification of conclusions from experience. This doubt and the foregrounding of imagination rather than reason as the source of expectation

constitute part of Hume’s skepticism toward the *inductive method*: An inductive argument supposes the generalization it aspires to establish and is therefore circular.

In the beginning of the twentieth century, empiricism was revitalized in the form of logical empiricism (see POSITIVISM). In general, logical empiricists shared an aversion toward metaphysical speculation and regarded observation and formal logic as means to justified knowledge. For logical empiricism, the scientific method differed from Newtonian induction. Instead, logical empiricism adopted the *hypothetico-deductive (H-D) method* in testing knowledge claims (see HYPOTHESIS TESTING). In this setting, knowledge was conceptualized as limited to observational propositions, and the validity of each proposition was assessed by its correspondence with hard empirical evidence. In other words, logical empiricism presupposed a natural unity between meaningful language and empirical facts. If a statement did not correspond to the observed facts, it was false, or meaningless at best.

Another attempt to reconcile rationalism with empiricism was classic American pragmatism, most notably formulated by Charles Peirce toward the end of the nineteenth century. Based on the philosophies of Kant and Hegel, Peirce’s philosophy formed a systematic critique of Cartesian rationalism and skepticism. Most importantly, American pragmatism attempted to transcend the real–ideal, mind–body, and material–immaterial dualisms inherent to both rationalism and skepticism by conceptualizing interpretation and the formation of knowledge from the viewpoint of biological evolutionism.

Informed by evolution theory, Peirce saw science as a self-correcting historical process. He stated that the objective of scientific inquiry is the gradual fixation of belief through induction. Beliefs can become indubitable for a number of undesirable reasons (popular beliefs held by the masses, or social force implied by an authoritative class of thinkers), but at times a surprising fact will force a revision of those beliefs. In pragmatist terms, induction depends upon the

confidence that a run of one kind of experience will not change or cease without some indication before it does so. Successful anticipation of these discontinuities in experience is essential to knowledge formation. For Peirce, the history of science had demonstrated that the probability in the long run to guess right far exceeds random luck.

Peirce introduced *abductive inference* as an essential logical function in hypothesis formation through guessing. When making an abductive inference, then, “we are bound to assume, independently of any evidence that it is true. Animated by that hope, we are to proceed to the construction of a hypothesis” (Peirce 1958, par. 219). In contrast to formal logic, Peirce’s extended view of logic adopted an empiricist attitude toward knowledge production, and abduction became one conceptualization of the logic of discovery and for the role of creativity (see CREATIVITY) in it.

Empiricism and archaeology

Due to the concrete nature of archaeological materials, empiricism forms a central theme in the epistemology of archaeology. Empiricism in archaeology, however, most often entails the conviction that the archaeological data can speak for themselves with no need for theorizing from the archaeologist’s behalf (Johnson 2011). Empiricist approaches in archaeology have tended to stress the relevance of excavation, data analysis, and common sense rather than theory or philosophy as primary sources of archaeological knowledge. Therefore, when speaking of empiricism in archaeology in particular, a distinction should be made between being empirical and being empiricist. While archaeology in general is empirical due to the nature of archaeological evidence and the hands-on character of its methodology, empiricism denotes a more specific genealogy of the epistemology of archaeology.

This genealogy has its roots in antiquarian and culture-historical archaeologies. These traditions are often referred to as naively empiricist because of their reliance on the inductive method. In this setting, archaeology centered collecting, with little regard for theory or source criticism.

Antiquarian and culture-historical archaeologies can therefore be seen as total archaeology that regarded the past as a collection of materials that had to be secured in their entirety before any general idea of the past could be reached. The view of nineteenth- and early twentieth-century archaeology as theory-free is, however, misguided because many archaeologists of that time also acknowledged the subjective extent of archaeological knowledge.

Epistemological issues about the limits of archaeological inference became increasingly addressed in archaeology around the mid-1900s. British archaeologist Margaret Smith (1955), for example, remained skeptical about the possibility of positive archaeological knowledge. The absence of a logical relationship between past human activities and the visible evidence that survives only partially led Smith and many others toward epistemic pessimism, especially when addressing questions that dealt with the less concrete aspects of past lifeways such as politics and religion. In essence, due to the lack of logical certainty between archaeological observation and archaeological explanation, Smith deemed archaeological inference a hopeless task. These developments led some archaeologists to call for more work on the explanatory level in the form of processual interpretation.

During the latter part of the twentieth century, processual explanation became a principal objective of New Archaeology. The proponents of New Archaeology adopted a more optimistic attitude toward epistemology and the role of theory in archaeology. In order to free archaeology from subjective speculation, the discipline was taken to follow the rigor of natural sciences rather than the descriptiveness of cultural history. The objective of New Archaeology was to render archaeology explicitly scientific by constructing an archaeological theory on the solid foundations of the logical empiricist conception of science (Gibbon 1989). One task of New Archaeology was to establish cultural laws analogous to their natural counterparts that could be used to explain unambiguously the unobserved cultural and natural processes relevant to the production of the observed fragmentary archaeological materials. Americanist archaeology in particular turned increasingly

toward anthropology in the construction of bridging middle-range theories between material culture as data and theories of past living culture (see *FORMATION PROCESSES*).

In the course of the twentieth century, logical empiricism faced increasing critique and gradually lost its appeal among archaeologists. Within the epistemology of archaeology, the liveliest critique was targeted against the vague formulation and the imagined neutrality of the H-D method adopted by many new archaeologists. Archaeologists were quick to point out that the H-D method was oversimplified, and actually utilized a range of inductive generalizations as well as analogical inferences. Archaeology was demonstrated to hinge on the supposed reality of a range of theoretical terms that do not correspond to any directly observable data. While a position by no means welcomed uncritically by all new archaeologists, the logical empiricist separation of theory from observation was subjected to fervent critique. Interestingly, one of the key figures of New Archaeology, Lewis Binford, argued that archaeological knowledge is a product of inferential reasoning rather than direct observation. Telling of the complex role of empiricism in New Archaeology, then, was Binford's repeated insistence that everyone was an empiricist apart from himself.

Increasingly, during the 1970s and the 1980s, archaeologists began to notice that observations are intimately theory laden and dependent on the social, cultural, and political context in which they were made. With the advent of post-processualism, many of the core assumptions of logical empiricism, such as the correct scientific method and the unity of sciences, became replaced with anti-positivist and constructivist alternatives, and philosophy of science went out of fashion in archaeology. Instead, archaeologists turned to semiotics and phenomenology for interpretative inspiration (see *INTERPRETATION*).

During the twenty-first century, archaeological empiricism has shown symptoms of revitalization. This development has happened on two interconnected fronts. On the one hand, the rapid development of exact natural scientific methods offers an attractive alternative to the atomized and at times confusing field of archaeological theory. Natural scientific methods yield a wide range of unambiguous data that,

for many, can render epistemological reflection about the nature of archaeological interpretation redundant.

On the other hand, the ontological turn that has taken place in much of philosophy and social sciences has resulted in a return to empiricism in the epistemology of archaeology. The "ontologically responsible" (Marila 2017) new empiricism, inspired to a large extent by new materialisms (see *NEW MATERIALISMS*) and speculative realism, presupposes a close affinity between ontological and epistemological concerns. The problem originating in ancient Greece that what is known (the object of inquiry) is dependent on how it is known (the method of inquiry) is not seen as a research deficiency but rather adopted as an epistemological starting point. The new archaeological empiricism is based on a pluralized conception of interpretation and holds that things-in-themselves, as they exist outside human understanding, remain constructed through their shared relations with multiple interpreting agents.

In respect to the archaeological material, new empiricism aims to sidestep the anthropocentrism of both logical empiricism and social constructivism. In part, this development has been inspired by the realization that new observations of the archaeological record can be so radically different and downright weird that reducing their meaning to rational or social representation would violate them. As new types of materials such as ocean drift matter and nuclear waste become regarded as archaeologically relevant, such archaeological key concepts as time (see *TIME AND TEMPORALITY*) and origin but also the theoretical and methodological core of archaeology need revision.

In order to react to the unexpectedness of the past, some realist archaeologists are turning to abduction instead of induction or deduction as an open-ended and speculative epistemological model for the logic of discovery and the formation of new archaeological knowledge. As a combination of empiricism and phenomenology, archaeology's new empiricism stresses the aesthetic and vague extents of knowledge formation as opposed to the view of the scientific method as inherently exact and rational. Perhaps somewhat ironically, then, philosophical new empiricist archaeologies continue

the methodological anarchism introduced in archaeology by post-processualism.

SEE ALSO: Knowledge and Inference;
Perception and Experience; Philosophy of
Science; Realist Philosophies of Science;
Symmetrical Archaeology

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Environment and Landscape

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It is not unusual in archaeology to begin the study of a site or region's history by reviewing or giving some kind of account of present-day, and past, environmental conditions. This often includes the geology, vegetation, and fauna, along with climate, and, on some occasions (such as at Newgrange, Knowth and Dowth in Ireland, Stonehenge in the United Kingdom, and some ancient Pueblo sites in the four-corners region of the United States), astronomical observations. These descriptions are usually presented as external conditions that help us better understand the physical contexts of the cultural sites in question. We thus describe the topography, soils, trees, and animals, rainfall and temperature, even the sun, moon, and stars, as a way to better identify the regional contexts of archaeological sites, and how those sites sit in a broader physical universe. We do so to better identify those outside conditions within which people are located—the “where” of the places that people did things in the past. Such descriptions of the physical environment are presented as a way to better understand the physical conditions that affected human actions. People did things through a combination of conscious intentions and subliminal influences, and those environments affected their decision making as constraints and opportunities of living in a material world.

Yet there is a problem with this view of human actions in the environment. In trying to understand the physical conditions of engagement—as this essentially divided dual “environment/people” way of conceptualizing human actions in place does—what we attempt

to understand are landscape engagements that are rich in cultural *meaning*. It is through this meaningfulness that people created individual archaeological “sites” as particular positionings of social actions. And it is also through meaningful emplacement that relations with nearby and more distant features (including other “sites”) are formed. Those meaningful locations are places whose social and cultural sensibilities archaeologists try to understand.

The concept of “landscape,” here used as shorthand for the totality of “scapes,” includes the land, water, and sky. The term “landscape” was first introduced into the English language during the late sixteenth century, when Dutch *landschap* artists depicted rural vistas as visual representations of domestic country scenes. Since the 1980s, Anglophone archaeologists in particular have become increasingly interested in anthropological and philosophical notions of “dwelling” (Ingold 2000) and “inhabitation” (Thomas 2008)—that is, of how cultures and social actions are located in particular world-views (ontological relations), of how human actions are acted out in a world made sense of through its meaningfulness, and by how the world is rendered in culture. No longer do we tend to reduce the past to the actions of “humans” who are more or less biological automata, individuals and individual societies who simply act to survive and whose behaviors at any point in time and place can be worked out simply by understanding the physical environments in which they hunt, gather, raise livestock, or grow crops. We have come to examine relationships between people and between people and things, how in the past people actively engaged in a meaningful world through the way they understood it to operate, and through how it is represented in culture. French archaeologists employ a term, “*le geste*,” to denote this human touch in, and of, the world. It is a useful word, without exact equivalent in English, although “gesture” comes close, because *geste* denotes how the things we do are socially inscribed with meaning. We can think of the hand that paints as a *geste*, as are the actions that lead to the making of a site. These involve intended, culturally

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informed, and socially sensitive actions, even if subliminal forces are also at stake and if the outcome is not exactly what was intended at the start. Archaeological objects, and archaeological sites, are gestural signatures; they are the “scapes” of cultural actions. This, then, becomes the key difference between the “environment” and “landscape” of the language of archaeology: At first the word “environment” was adopted as a way of describing the physical environment that surrounded and affected human actions; and, later, “landscape” emerged as a way of nuancing more the notion that from the outset people are born into already-meaningful worlds (sometimes explicitly expressed in Heideggerian phenomenological terms, as “being-in-the-world”), so that to understand actions we need to understand their meaningfulness as much as we need to understand the material properties of things.

Let us give an example of how place is inhabited in this cultural way, how its imbued social meanings help structure social engagement, by reference to Australian ethnography. Our aim here is to demonstrate how what is often thought of as external environment is in fact more than this when dealing with the actions of people, with human *gestes* and cultural history. Landscapes are meaningfully engaged and understood through world-views that we can think of as both ontology (the way we understand the world to *be*) and cosmology (in archaeology, this term is usually used in a way that nuances the mysteries and esoteric/spiritual constructs of cultural groups, unlike in western astrophysics where it refers to those dimensions of astronomy that concern the physical structure and evolution of the universe). Those world-views guide the ways people think about and act, so much so that archaeological sites become structured not just by the lay of the land as physical phenomena, but by the lay of the land as ontologically ordered phenomena.

The anthropologist Marcia Langton (2002) gives a useful night-sky analogy to illustrate the point. What we see in the sky are not only planets, stars, and other physical bodies, but something much grander: a confirmation of what we already know about how the world operates—time, life, our place in the universe. What we see as tiny bright dots on a black, blank canvas, we know to be gigantic balls of fire whose light emanates across space as time progresses, literally at the

speed of light, reaching us in the here and now as the night-sky that we gaze upon. It is not simply that we see these cosmic realities with our own eyes and so we believe, but rather we already understand this to be the case as we gaze at the stars; the stars are already there as meaningful entities. What we see is not abstract visual space, but rather cultural places already rich in meaning, in this case informed by astronomy and related disciplines.

But this is not the only way of seeing the night-sky. In Aboriginal Australia, the trees and hills and fauna, and the stars, are emanations not of western botanical, geological, zoological, or astronomical knowledge, but of the numinous ancestral forces that give shape to place as *country*, the meaningful homeland into which all things are given their defining characteristics in the creative events of “the Dreaming,” a landscape that is as much kin as it is “environment.” Those kin relations that people have with the sky, for example, affect everyday life here on earth, for they intimately connect people with topographic features created by the ancestral beings. All of society is implicated by those features, because the ancestral beings have particular kinds of relationships with everyone (everyone is connected with individual places through those particular ancestral connections), and everyone is connected with each other in specific ways. Those connections demand exacting forms of behavior—the social rules and guidelines reported by community members and social anthropologists. The ontological, social connections between people and features of the landscape affect what people do in particular locations, and this helps structure the archaeological record of each and every site.

For example, in the ethnographic traditions of Australian Aboriginal and Torres Strait Islander cultures, social life (including, but not reducible to, subsistence) is intricately linked to the sky. Many traditions explain that what is on the land is connected to, and reflected in, the sky. Torres Strait (the island-clad sea between northeastern Australia and the southern New Guinea coast) Islander ways of being and ways of knowing are closely connected to the stars. Islander cosmology is based on the story of the culture hero Tagai (Sharp 1993). Tagai was a great fisherman and warrior. During a fishing expedition with his crew

of twelve men (Zugubal) and his first mate Kareg, Tagai searched the reef for a suitable fishing spot. Hot and frustrated, the Zugubal consumed Tagai's rations, angering him upon his return. Tagai killed the Zugubal, who were cast into the sky (after being drowned) as two groups of stars: Usiam (the Pleiades star cluster) and Utimal/Seg (the belt and scabbard stars of Orion). Tagai and Kareg went to the opposite side of the sky to keep away from the selfish Zugubal. Tagai comprises several western constellations spanning across the sky from the Southern Cross (Crux) to Corvus, standing on his canoe (Scorpius) with Kareg (the star Antares) at the stern.

The story of Tagai encompasses themes that provide instruction for laws and customs that inform Islander identity and spirituality. These themes influence social-cultural traditions, but also describe knowledge about the interplay between Islanders and the places in which they live (Sharp 1993, 3–5). The Tagai narrative establishes connections between the rising and setting of stars at dusk and dawn throughout the year and their connection to changing seasons, which inform weather, climate, food sources and means of procurement, social events, and how people see the world to operate generally. In doing so, they affect how people engage in places, and thus how and why (archaeological) sites are formed. Islander epistemologies draw upon causal relationships between the land and the sky. For example, as the Zugubal rise in the evening sky, they announce their presence with thunder, signaling the coming of *kuki*, or monsoon season (Eseli et al. 1998). During this time, Tagai and Kareg set in the west. As they set into the sea, they splash water into the sky, which falls as the rains of the monsoon season (Sharp 1993, 60).

This knowledge is encoded in song, dance, and ceremony, which incorporate masks and dance machines and are often performed at sacred sites at significant times of the year. The Kek ceremony on Mabuyag is performed when Kek, the yam star, rises in the dawn sky just before sunrise (Haddon 1904, 339). Regarded as the Islander New Year by many communities, the rising of Kek at dawn signals the approaching dry season, the southeasterly winds, and the time to harvest yams. The Kek ceremony is performed at a site on the southeast coast of the sacred islet of Pulu off the western coast of Mabuyag. It serves as

a sign of thanks and as an increase ceremony. The ceremonial ground on Pulu faces the star as it rises in the southeast over Baudhar (Mount Augustus) on the nearby island of Mua (Haddon, Rivers, and Ray 1912, 223). This is all part of the Torres Strait landscape, but in archaeology it would not normally be treated as a description of the environment.

Similarly, in Aboriginal traditions of the ethnographic period across much of Australia, ancestral beings created the world before ascending to the sky, where they watch over the world as stars and planets. Their actions are often denoted by transient celestial events, such as comets, meteors, aurorae, and eclipses, particularly as warnings to obey sacred law. Many beings are represented not by constellations of stars, but by “dark constellations” traced out by the dust lanes in the Milky Way. Among the best known and widespread examples is that of the celestial emu. The emu's head is represented by the Coalsack nebula, which borders Crux. The neck stretches down through the constellation Centaurus and the flightless bird's body is the galactic bulge of the Milky Way in Scorpius, with its legs stretching down through Sagittarius.

In Euahlayi traditions of northwestern New South Wales (Fuller et al. 2014), the emu first appears in the evening skies during April and May as a female chasing a male for mating. In June–July, when the emu is higher in the sky, it represents a male sitting on the nest. This is when eggs can be collected as a food source. In November, when only the bum of the emu is visible in the sky, the emus are sitting in waterholes. In the summer, the sky emu mostly disappears, meaning the emus are leaving the waterholes as they dry up (Figure 1).

The celestial emu also informs ceremony through connections between the land and the sky. Many initiation sites in southeastern Australia comprise two circles connected by a pathway. The ceremonial ground is reflected in the Milky Way as the celestial emu (Fuller, Hamacher, and Norris 2013). Many initiation ceremonies in southeastern Australia are held when the sky emu aligns with the terrestrial ceremonial ground as they link on the horizon in the southwest. This coincides with August and September, when emu chicks have hatched

and are nurtured by male emus. This symbolizes the elder men bringing the boys into manhood through initiation.

Many of these ceremonial sites have been identified and mapped during field surveys by archaeologists. Today, we make sense of them through the ways people engaged with *their* world—that is, through notions of “landscape” as cultural constructs, more so than “environment” as fixed and all-endearing entities—for it is in the way that people related to the stars, to the land, and to each other as connected beings that the archaeological sites can be understood as

social and cultural places. Landscapes express place and emplacement as ontologically informed and socially engaged. And, through time, it is those shifting constructs that archaeologists investigate. We can, and do, look at all kinds of places through this landscape lens: at broad geographical scales, how people interact across wide expanses of sea, such as in the western Pacific where Lapita colonizers made far-flung places their own, culturally and socially domesticating space in the process. At a smaller geographical scale, we explore how new social worlds were made when people built stone or earth channels

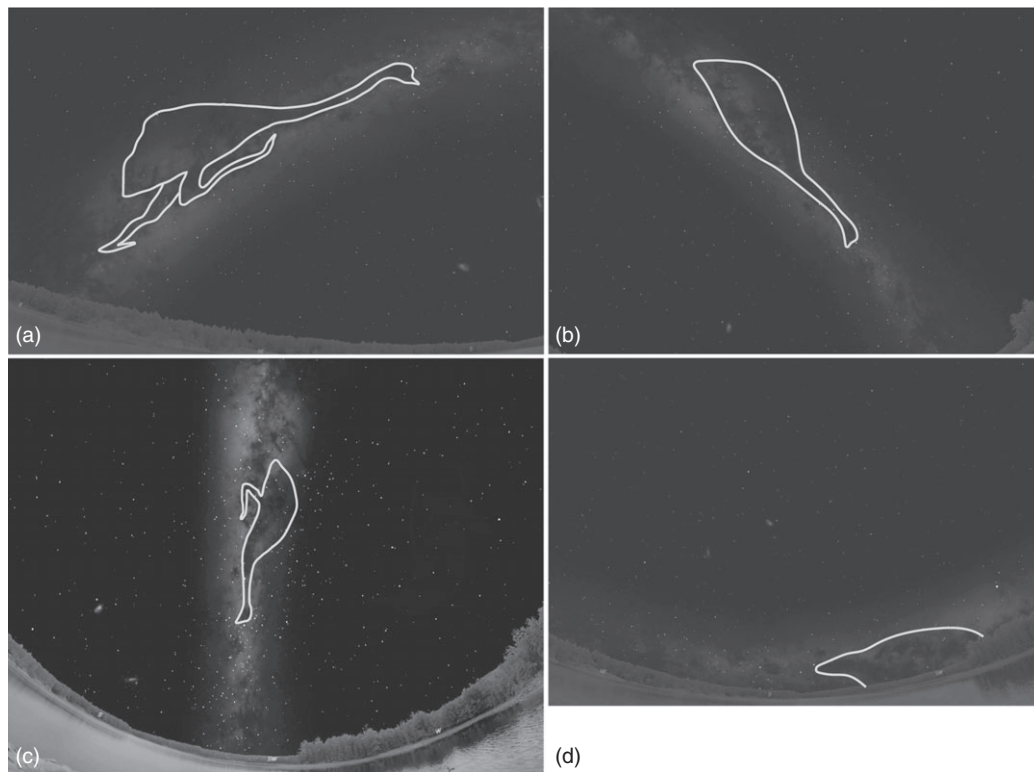


Figure 1 Changing view of the emu in the sky, according to Euahlayi Aboriginal traditions (New South Wales, Australia). (a) Female emu chasing a mate. (b) Male emu incubating eggs. (c) Eggs hatch and male emu begins rearing the young. This occurs during the time of year when male initiation ceremonies are undertaken. Sacred *bora* grounds where initiation ceremonies are performed align spatially with the axis of the celestial emu, which itself represents the sky *bora*, creating a pathway from earth to sky through the Milky Way in the southwest. Here the place of social activity (identified by archaeologists as a particular kind of “site”) was created by reference to local indigenous cosmologies. (d) Emu sitting in a waterhole in late spring. The emu leaves the waterhole as it dries up in summer; this is a time when the celestial emu dips below the horizon.

Source: Images published with permission of the authors, Fuller et al. (2014).

as conduits for flood waters populated with eels, allowing the mass capture of eels and creating new seasonal schedules and networks of social interaction in the process (e.g., McNiven et al. 2012). At a smaller scale still, individual sites are now examined for how people are implicated in them, and, in doing so, how the very fabric of the sites progressively changed and grew through those social engagements, such as at Nawarla Gabarnmang (Australia) and Chauvet Cave (France) (Delannoy et al. 2013) and barrows of the British landscape (e.g., McFadyen 2008). The archaeological sites are architectural locations where people undertook, and engineered, socially and culturally meaningful actions. In “landscape,” the environment is not simply outside, but also inside; nor is it simply about the navigation of terrain towards the consumption of “resources” as food—the starscapes of Torres Strait Islander and Aboriginal peoples illustrate this point nicely. Rather, by examining spatial and temporal patterns in the products of past social and cultural engagements at varied geographical scales, the history of the meaningfulness of “the environment” as landscape, of the *gestes* performed, allows us to better understand the human past.

SEE ALSO: Heritage and Landscapes; Inhabited Landscapes

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Ethics in Conservation

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Ethics are future-oriented rules of behavior based on ideas about what are morally correct actions—those that are right, just, and good, and create just actors in return. Codes of ethics are sets of rules agreed upon by a particular group, and when ethical positions are stated, it is important to provide context for the group and their beliefs. As a practice aimed at long-term safeguarding, preserving, and communicating heritage values to present and future generations, heritage conservation, particularly in heritage practice or management, is intimately tied to ethics, and is often spoken about in moral terms as ensuring the public good. Yet the nature of heritage, as well as the complexities of conservation in specific contexts, makes the application of ethical principles in actual practice quite challenging. While heritage purports to be inclusive—it links people with a recognized claim to an object, site, or intangible production through time and space—it does this by being necessarily exclusive; heritage claims identify the object as being valued and meaningful to a specific group and thus not to others. Conservation practice therefore entails remembering, emphasizing, and prioritizing certain narratives about a heritage property while forgetting, deemphasizing, and marginalizing others. Conservation practice can also be physically destructive: as particular qualities are preserved and enhanced, physical elements testifying to other phases of the object's life history are removed and destroyed. That these actions are just or unjust is not inherent, but are situationally determined through what ethicists call “morality.” The difference between ethics and morals is that ethics are philosophical ideals guiding social actions, while morals, which are linked to

the norms of society or particular groups within societies, are the ways in which ethical ideals play out in specific instances. The challenge in heritage conservation is to identify an overarching ethical stance that can accommodate different, and sometimes conflicting, practical applications.

Because of the complexity of heritage conservation and the many actors that are affected by it, groups involved with conservation activities (here more broadly defined as heritage preservation/heritage management) have developed codes of ethics that serve as general guidelines to regulate specific activities. They regulate ideas of ownership, use, and communication of heritage values, and often identify these by specific groups of stakeholders. From a discursive perspective, the original, often indigenous producers of tangible or intangible heritage are usually the primary stakeholders defined. But in reality, a broader definition of stakeholder could include the proponent of an activity (e.g., a developer, bank, community, government agency/entities), places where heritage materials are “stored” and/or exhibited (e.g., museums, archives, libraries, and other types of repositories), entities that manage or interpret heritage (e.g., heritage management firms, universities, site managers, travel industry professionals), entities that have a mission to “safeguard” heritage or a philanthropic interest in it (e.g., professional societies, nonprofits, including nongovernmental nonprofit organizations, religious institutions, and intergovernmental organizations (such as the United Nations' Educational, Scientific and Cultural Organization [UNESCO] and its professional advisory bodies like the International Council on Monuments and Sites [ICOMOS] and the International Union for Conservation of Nature [IUCN]), organized conservation or heritage societies, conservation-minded donors), and the many publics that “consume” heritage (e.g., tourists, pilgrims, government agencies/entities, taxpaying citizens). If the desired outcomes of situations are always focused on the “best” or most appropriate treatment of tangible or intangible heritage resources, then ethical practice would

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be more straightforward. But herein lies the crux of the problem—almost all of the stakeholders have conflicting, often quite different ideas about the most desirable outcome(s) from their perspectives. These center around disagreement regarding the value, ownership, and uses of heritage, and the appropriate ways to communicate and “manage” it. Stakeholders often struggle and negotiate with each other for power to dictate the outcomes of these areas of conflict.

Di Giovine (2015) lists three different ethical paradigms in conservation practice: paternalistic, multicultural, and patrimonial. Paternalistic ethics are in play when those in privileged and/or dominant positions assume a stewardship role over the heritage property and its conservation plan. As these are often archaeologists and heritage managers—the community of practice invested with the authority to care for these properties—they are frequently informed by a Eurocentric worldview that privileges care for the authenticity and integrity of the material. This object-centric worldview comes into conflict with other stakeholders’ worldviews, such as those in concept-centric societies, as discussed by Christina Kreps (2003, 46–48). Buddhist practices, for example, are guided by an understanding of the impermanence of life, and therefore often let what would be considered heritage resources naturally decay. Deeper cognizance of differences and self-reflexivity in archaeology in the latter half of the twentieth century has fostered what Cristóbal Gnecco (2014) considers to be multicultural ethics, which aim for more inclusivity and consultation in decision-making processes. Yet multiculturalism comes with its own critiques, as it emphasizes the “otherness” of nondominant stakeholder groups, and, in doing so, solidifies the hegemony of the dominant group. As a response to this, patrimonial ethics is a paradigm that acknowledges the life history of a tangible or intangible heritage resource (e.g., an object, building, site, landscape, or custom) and its multiple and negotiated uses and meanings. To better understand what kind of actions are just and good toward a heritage resource in its present state, stakeholders would be identified and meaningfully empowered to determine the heritage property’s conservation outcome.

Paternalistic ethics

Paternalistic ethics are those idealized actions that position the conservator over other stakeholders as a privileged, guardian figure toward the material protection of cultural property. Inasmuch as archaeological, museological, and artifact/document conservation practices have their origins in western, European history—and are exported throughout the world via globalization as a marker of modernity (Kreps 2003)—it continues to be the hegemonic ethical orientation for conservation practice today.

Like anthropology and archaeology, the development of the heritage industry and conservation practices are deeply rooted in the nineteenth-century colonial system and its paternalistic quest to civilize and modernize native groups who were perceived to be evolutionarily behind that of the West. The changes the colonial system wrought on perceived traditional ways of life, coupled with fin-de-siècle fears of their own societal decadence and loss at the hands of modernization and industrialization, produced the impetus for salvage or rescue archaeology and conservation in the late nineteenth century, and influenced future perspectives on responsible management of the archaeological record. The earliest uses of the word “heritage” (in England) or *patrimoine* (in France) referred to the creation of a national office to protect historic monuments and artifacts—a dual process of recovery (i.e., excavation and conservation/preservation) and discovery (i.e., archaeological and historical practice aimed at fleshing out the roots of modern society). Furthermore, informed by Enlightenment-era notions privileging the visual over other senses, Victorian-era scientists and early museum curators also espoused the philosophy that an object (or fragment) can elucidate obscured historical, cultural, and biological facts if interpreted by a trained expert. There was little reflexivity as to the subjectivity of the expert interpretation. Such a notion privileged material authenticity and integrity, and largely influenced developing notions of western notions of stewardship.

Artifact-centered, the paternalistic ethic of conservation was, and continues to be, motivated by a notion of “risk,” of a threat to the integrity

of an object by outside forces (including time itself). It is because of these risks and threats that heritage properties are considered to be of heightened value. Conservation and heritage resource management developed significantly in the second half of the twentieth century, as practitioners sought to salvage and restore cultural properties damaged as a result of devastating warfare, and as newly independent colonial states began to see their traditional heritage as valuable resources, particularly in raising development funding and in capitalizing on the growing tourism industry. At the same time, legislation designed to protect and manage heritage before it was destroyed by development or other means began to be enacted throughout the world.

Representing the culmination of these movements, UNESCO ratified the 1972 World Heritage Convention, which saw cultural heritage as a prime mobilizer of global solidarity and thus of fostering peace at the grassroots level. UNESCO had successfully mobilized the international community to save the monuments of Ramses II in Abu Simbel, Egypt, which would have been destroyed by the construction of the Aswan High Dam, and then raised funds to “Save Venice” from rising floodwaters. As both of these catastrophic events generated impassioned responses from nonlocal people at the grassroots level, UNESCO saw the potential in creating global solidarity by constructing an international consensus of certain sites’ “universal value,” and therefore of the collective responsibility for safeguarding them. The World Heritage Convention—and its associated Intangible Cultural Heritage Convention in 2003 protecting traditional practices and performances—are therefore ethical documents, paternalistically aimed at “responsibilizing” populations (Ilcan and Phillips 2006, 64) and motivating them to act in ways that are right, good, and just—not only toward the heritage resource itself, but also toward one another.

Despite a greater emphasis on diversity and acceptance of many societies, UNESCO and its Advisory Body, ICOMOS—like other conservation organizations—employs a paternalistic ethic toward conservation. World Heritage properties are evaluated against a rubric that specifically assesses the authenticity and integrity of material remains, as well as how effectively the property reveals, or illustrates, historical or cross-cultural

connections. Despite an increased awareness of the role of local communities in heritage conservation, World Heritage Sites’ nomination, designation, and care are ultimately in the hands of the nation-state, which works with these supranational organizations in designing conservation plans. Furthermore, the unit of measurement of this ethical paradigm focuses not on the preservation of indigenous community or diverse cultural groups per se, but of a hegemonic community modeled in the likeness of UNESCO. This community is not a traditional empire or sovereign nation-state, but what Di Giovine (2009) has called the *heritage-scape*: a dynamic, borderless imagined community predicated on the ritual reappropriation and juxtaposition of tangible heritage sites.

Multicultural ethics

Following the reflexive turns in historiography and anthropology, and born of the Euro-American “multiculturalism” movement of the second half of the twentieth century, heritage theorists have become critical of their disciplines’ own historical role in the colonial (and now neoliberal) endeavor, as well as their own paternalistic ethics marking their work, which solidify authorized or official discourses about the heritage property. As a result, archaeological and museological societies have embraced what Gnecco (2014) termed “multicultural” approaches, which aim for inclusivity in conservation practices by involving local actors in conservationists’ projects (often as a labor force), opening local museums for the benefit of making their finds more accessible to the surrounding population, and integrating alternative historical understandings in their interpretations. Seemingly in contrast with paternalistic ethics, Kreps (2003, 10–11) argues that “new museology,” which embraces a multicultural paradigm, is “people-centered and action-oriented” and suggests co-curation and other forms of indigenous involvement in the conservation and exhibition processes.

While multicultural ethics embrace inclusiveness and diversity of perspectives, critics like Gnecco note that it does little to change

conservation in practice. Like Talal Asad (1993), Gnecco (2003, 20) points out that multiculturalism also traces its origins to the colonial era, in which diverse “others” were “clearly defined, delimited, separated” and stereotyped so as to facilitate their assimilation into the dominant culture under the rubric of “diversity.” For Asad (1993, 245), multiculturalism acknowledges that these clearly defined minority groups are given “the right to make a contribution” to society by the dominant culture. Terrance Turner (1993, 414) argues that, at best, multiculturalism can be conceived of as “an agent of change” in indigenous societies that provides a framework for contesting hegemonic influences, or at worst becomes “difference multiculturalism” aimed at reifying and fetishizing ethnic or cultural differences that give license to political and ideological separation. Either way, despite the oft-good intentions of conservationists, multicultural ethics—predicated as they are on identifying “cultural difference” within a culturally dominant society—often thus serve to extend the hegemony of the dominant group, because, ultimately, the hegemonic power determines the norms and values to be incorporated and coordinated. With this paradigm, conservators and heritage managers run the risk of imposing their “multicultural” values on other groups that may not share it. Ensuring that other groups are consulted, that others are educated or provide input on conservation practices, or that the practices benefit locals continues to position conservators as the patriarchs, so to speak, in the paternalistic ethical paradigm. Multicultural ethics often create, or perpetuate, the very tensions that it purports to resolve.

Patrimonial ethics

Both ethical paradigms seem to moralize conservation and thus valorize conservationists and, at the same time, call into question the morals of preservation practices as they affect others. Both therefore tend to obscure or lose focus on the heritage object itself. Patrimonial ethics, however, are centered on a more robust understanding of the totality of stakeholder groups in a heritage discourse, and refocus on the heritage property (Di Giovine 2015). They recognize that, as Pierre

Bourdieu (1993, 34–35) states about a work of art, a heritage object is not the product of a single author or stakeholder community, but the “result of coordinated activities of all the people whose cooperation is necessary in order that the work should occur as it does.” He defines these coordinated activities—and the socioeconomic space that contains them—as a field of cultural production. The perspective of patrimonial ethics thus sees broader relationships between the object and its stakeholders, and between the symbolic and lived uses of the heritage property.

Stemming from the notion that heritage objects or resources gain meaning through their social contexts and uses, patrimonial ethics treat them as social actors in their own right, able to impact and shape social relationships. Patrimonial ethics look to prescribe appropriate treatments of the object as well as how to act toward other stakeholders. This requires a more expansive understanding of the history and social structure of conservationists’ engagement with the heritage object as taking place within a field of production through which a variety of stakeholders are involved in constant struggles and negotiation regarding the meanings, values, and usages of particular heritage sites. It also understands that there is not one “heritage industry” or a universal guideline on ethical conservation practices, but rather that each heritage site or object is situated in its own context, and that each has a unique field of stakeholders. Each of these stakeholders constitutes a particular community of knowledge and practice, and the object can assume multiple meanings and uses depending on the different bodies of knowledge associated with it. Understanding that conservationists/preservationists represent but one out of many stakeholders in this field, and that they espouse but one body of knowledge concerning the object, a patrimonial position on heritage is more reflexive and seeks to assess key players and their engagements with each other and the resource itself. Furthermore, because it focuses on the good of the object, rather than solidifying the hegemony of the conservation community, patrimonial ethics should empower (not simply “involve”) local communities to determine the key significances of the object to be conserved. This does not mean that the community’s decision always takes precedence—frequently not

all stakeholders' ideas will align—but that there should be true negotiation of, and co-creation of a plan for, conservation. Rather than beginning with the assumption that alternative voices should be integrated into a preexisting conceptual framework, patrimonial ethics consider that there are multiple architectures of significances that will inevitably overlap—and that understanding this will better inform what is “right, fair, just, or good” for the object and the other stakeholders in a particular context.

Challenges

In practice, applying the tenets of patrimonial ethics will be difficult in cases where heritage practice already dictates, often within the context of legislation, how stakeholder interaction will occur and how decisions regarding heritage conservation will ultimately be made and by whom. This also includes areas where democratic actions—such as voting on the removal of contentious monuments from the public sphere—may be marked by structural inequalities that favor dominant groups, or that are highly contested by different factions. Working within current established practice and taking opportunities to change or improve it by incorporating more reflexive positions will involve establishing and rebuilding current, often dysfunctional relationships among those involved in heritage conservation.

SEE ALSO: Archaeology and the Present; Community Heritage; Critical Museology; Critical Theory; Cultural Resources Management; Heritage: Nonwestern Understandings; Heritage and Community Archaeology; Heritage and Conflict Resolution;

Heritage and Economics; Heritage and Human Rights; Heritage and Landscapes; Heritage and Policy; Heritage and Politics; Heritage and Sustainability; Heritage and Value-Based Approach; Heritage Ethics; Material Culture; Public Archaeology; World Heritage Sites Designation

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Ethnoarchaeology

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Ethnoarchaeology is the ethnographic study of relations between people and material culture. It is a specialized ethnographic method developed to facilitate the use of ethnographic analogy in archaeological interpretation. Ethnoarchaeology as an iconic subspecialty in archaeology was given its most influential definition as part of the New Archaeology in the United States, but the more general tendency for archaeologists to critically investigate the sources of analogical inference by conducting ethnographic research has a much longer history and is found globally.

Ethnographic research by archaeologists developed primarily to address two issues that archaeologists have encountered in making interpretations about the past. First, archaeologists have expressed some anxiety about their ability to interpret the material record directly, that is, by using analogies drawn primarily from their own background experience. They worry that their standpoints in “modern” post-industrial societies leave them ill equipped to understand material patterns in the archaeological record that may reflect radically different lifeways, including “pre-modern” foragers, subsistence agriculturalists, and craft producers. As a result, archaeologists have sought to consult supplemental bodies of knowledge that might assist them to understand economies, social systems, political structures, and religious beliefs that are not part of their own cultural repertoire. Second, while cultural anthropologists, post-colonial researchers, and indigenous scholars have produced extensive literatures that shed light on other ways of being in a range of societies, they have tended not to investigate the material implications of the practices they describe. Insights from these studies have inspired theoretical innovations across the social sciences, but archaeologists find them difficult to apply systematically to

the interpretation of the archaeological record. Together, these two issues create a need for archaeologists to conduct their own forms of ethnographic research. Ethnoarchaeology might then be defined as ethnographic fieldwork by archaeologists who (1) investigate alterity by studying “others” with lifeways that are perceived to be both different enough from the experiences of archaeologists and similar enough to ancient settings to warrant investigation; and (2) carefully consider the material implications of the practices they document so their existence in the past can be inferred from archaeological remains. As Nicholas David and Carol Kramer (2001) have noted, this definition makes ethnoarchaeology an explicit attempt to expand the analogical consciousness of archaeologists.

At its core, ethnoarchaeology is a specialized subfield that aims to address archaeology's reliance on ethnographic analogies to interpret the archaeological record (Gould and Watson 1982). Analogy is the transfer of knowledge from a well-known source context to a lesser-known subject context, for the purposes of interpreting activities in the subject context. The transfer of knowledge from source to subject contexts begins from an initial abduction that suggests that some observed similarities between the two contexts makes them alike in other, often more fundamental ways. Testing is undertaken to assess the suitability of the original interpretation by seeking evidence for the additional similarities and differences that should be present if the original analogy is valid (Wylie 1985). In archaeology, analogical inferences are often based on similarities in material culture between contemporary and ancient contexts, which suggest that similar causal mechanisms were responsible for those patterns. The background theoretical interests of the interpreter, including existing theories about behavioral-material correlations, tend to define which similarities are considered significant enough to warrant further analogical treatment (see below). Interpretive security is then created for the initial inferences through subsequent analogically based tests that elaborate on the causal

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antecedents for the material patterns under investigation, producing increasingly refined understandings of both contemporary and ancient settings (David and Kramer 2001, 47–48).

For example, cultural historical archaeology has often suggested that stylistic dimensions of pottery such as decoration reflect different archaeological cultures. Cultural historical archaeologists may then believe that an archaeological pattern in which unique decorative traditions are imbricated across an ancient landscape reflect the presence of distinct ethnic communities who trade pottery across supposed ethnic boundaries. The accuracy of this initial inference can be assessed through secondary testing both in the source context by ethnoarchaeologists and in the subject context by archaeologists. Ethnoarchaeologists might initiate targeted studies of craft transmission, production sequences, decorative symmetry, or ceramic marketing and consumption to document ethnicity's impact on ceramic production and distribution in a selection of contemporary societies. Archaeologists working on the subject side of the analogy can draw from this additional knowledge to further test their initial interpretation against the same ceramic collections by seeing if new lines of evidence support an interpretation of ethnic heterogeneity. Ceramic petrography might identify, for example, compositional patterns indicating different production sequences or distinct sources of raw materials, transforming an initial interpretation about ethnicity into a more precise assessment of communities of practice or systems of ceramic distribution. Beyond ceramics, testing on both sides of the analogical equation might shift to other materials that ethnoarchaeologists have shown can vary with identity, such as iconography, architectural styles, or cuisine. The testing of different lines of evidence in both archaeological and ethnoarchaeological settings may support, transform, or even refute the initial analogy.

Over the long term, these distinct source side and subject side tacks allow archaeologists to refine their inferences about the past. Analogical inference is key to a post-positivist approach to epistemology that builds interpretive security in archaeology by triangulating independent lines of evidence, each drawn from some component of

source-side analogical knowledge to understand both human action and material patterns (after Wylie 1985). Ethnoarchaeology and archaeology are thus complementary research strategies, and research interests in ethnoarchaeology necessarily mirror topical interests in archaeology. Historically, ethnoarchaeologists have emphasized studies of formation processes, activity areas, craft production, architecture, space use, subsistence practices, discard and recycling of artifacts, and typology (David and Kramer 2001, 14–31; Lane 2006, 406–416).

The emergence of ethnoarchaeology

Archaeologists globally have used ethnographic information to assist their interpretations. However, “ethnoarchaeology” as a distinct research strategy is most closely associated with the New Archaeology that appeared in the United States in the 1960s. New archaeologists and later processualists felt that ethnoarchaeology should produce middle-range theories, made up of behavioral–material correlates that would allow the archaeological record to be translated into the behaviors that were the focus of their epistemology. This view of ethnoarchaeology subsequently diffused globally as an interest in formation processes of the archaeological record.

The intellectual history for ethnoarchaeology, however, goes back to at least to the Renaissance and the sense that “others” encountered by European explorers might inform understandings of European pasts. Formal analogical parallels between archaeological and ethnographic communities became most clearly defined in the late nineteenth century with classic evolutionism. Lewis Henry Morgan and Edward Tyler argued that cultures accumulated cultural “germs” through time and went through a common set of evolutionary stages, stretching for Morgan from savagery through civilization. Living societies could then be a basis for interpretation of archaeological remains when they shared a similar stage of development. The turn of the century cultural historical anthropology of Franz Boas reflects a widespread rejection of this classical evolutionary tradition and its emphasis on comparative forms of analogy. Yet, ethnoarchaeology was

given its first formal definition at that time by Jesse Fewkes. Consistent with the broad tenets of Boasian culture history, Fewkes relied on direct historical analogies in which oral histories from Hopi communities were used to understand nearby Tusayan archaeological sites. Subsequent work by Maxine Kleindienst and Patty Jo Watson in the Near East and by Robert Ascher in Sonora initiated a tendency, still prevalent in archaeology, for historical ties to be the primary basis for analogical inference (David and Kramer 2001; Lane 2006).

Ethnoarchaeology as a focused research specialty emerged as part of the New Archaeology in the 1960s. The neo-evolutionary focus of the New Archaeology meant that societies were expected to be broadly similar when they shared common adaptive strategies and sociopolitical organizations, and thus general forms of analogy were once again encouraged. At the same time, ethnoarchaeology was given a key role in processual archaeology's broadly positivist orientation. Ethnoarchaeology would produce middle-range theories made up of behavioral-material correlations that could be directly inserted into archaeological testing regimes to produce a methodological form of objectivity (Cunningham 2009). The hope was that the behavioral-material correlates ethnoarchaeology identified would produce a nearly universal set of material translations for human behaviors. While source-side experimental work found material patterns that could be consistently correlated to human actions because they were prescribed by natural laws, such as those found in lithic usewear or organic residue patterns, ethnoarchaeology generally failed to identify similar correlates for more complex social phenomena. Instead, ethnoarchaeologists produced cautionary tales that showed the diverse ways that human actions impacted material patterns.

By the early 1980s, post-processual archaeology sought alternatives to the ecological determinism of the New Archaeology by exploring structuralist approaches to meaning through a series of ethnoarchaeological studies in east Africa and India (contributions to Hodder 1982). Later, post-processual work distanced itself from the term "ethnoarchaeology," which it attributed to processual archaeology's neo-evolutionism, and instead introduced "material culture studies"

for its own consciousness-expanding research. While processualists generally saw material culture as "symptomatic" of behavioral systems and ethnoarchaeology as a way of translating material patterns back into behaviors, post-processual research considered material culture as actively constitutive of social relations. It thus used practice theory as a framework for reading cultural meanings directly from material patterns. Post-processual archaeology's focus on European prehistory also meant that it was ambivalent about the need to use "others" as a source for analogies, and instead archaeologists drew from their own experiences in post-industrial European society to interpret Europe's more remote pasts. Frequently this was accomplished by using universal or nearly universal processes associated with materiality as a basis for inference such as objectification, inalienability, and material agency. The coupling of this approach with a relativistic epistemology also meant that post-processual archaeologists were not as preoccupied as processualists had been with verifying their interpretations using programs of source-side testing. Consequentially, ethnoarchaeology waned in post-processual archaeology as other forms of ethnographic research blossomed under different rubrics. These included not just material culture studies, but also ethnographic studies of archaeological practice and a series of well-developed research programs that integrated ethnographic, archaeological, and historical methods into detailed studies of the ties between contemporary experience and archaeological heritage, such as archaeological ethnographies and indigenous archaeologies (e.g., Hamilakis 2011; Politis 2015). While post-processual scholars generally avoid describing their work as being in any way "ethnoarchaeological," their suite of approaches nonetheless reflects parallel attempts by archaeologists to expand their analogical consciousness through ethnographic engagements.

Global ethnoarchaeology

Work outside the Anglo-American tradition has shown similarities and some important differences (see contributions to Marciniak and Yalman

2013). Globally, archaeologists seem to have responded to their sense of analogical myopia by carrying out ethnographic fieldwork and historical investigations. Continental European folk culture approaches to analogy developed early and paralleled culture history in the Americas. In Italy, Poland, Russia, Germany, Turkey, Egypt, and Bulgaria, rural peoples who maintained supposedly “traditional” lifeways were studied by archaeologists to provided source-side inspiration for archaeological studies. Typically, these studies emphasized craft production systems or subsistence practices such as peasant agriculture or pastoralism that were unfamiliar to archaeologists and seemingly reflected continuities from ancient folk cultures in the same region. This use of historically focused analogies was often sporadic, but in Germany “ethnoarchaeology” was part of a long history of research in ethnohistory that includes explicit concerns with analogy. By the 1980s, the Anglo-American perspectives on ethnoarchaeology began to influence local folk cultural approaches. In the Turkish context, ethnoarchaeology was introduced in part by foreign projects, whereas elsewhere it emerged among local scholars who began reading Anglo-American publications. The comparative late arrival of ethnoarchaeology in Italy and Turkey meant that processualist and post-processualist insights were often incorporated simultaneously and produced diverse forms of ethnographic research by archaeologists.

Other areas have developed and maintained distinct forms of ethnoarchaeology (again, see contributions to Marciniak and Yalman 2013). In Francophone Europe, logicist approaches inspired by J.-C. Gardin produced a vibrant tradition of research that uses formal interpretive procedures to identify analogs in ethnographic research and apply them archaeologically. These exist alongside an equally well-developed Francophone interest in the anthropology of techniques that uses *chaînes opératoires* to understand how production sequences relate to broader social phenomena. In the former Soviet Union, Marxist archaeology initially emphasized the reconstruction of the forces and relations of production by drawing analogs from a broadly comparative sociological approach rather than ethnography. This was later supplanted by the

stage-based approaches of historical materialism in which ethnographic populations and archaeological materials were considered generally comparable when they possessed the same mode of production. Recent Russian research combines archaeological and ethnographic research on specific communities alongside ecological and experimental studies. In China, a distinct approach to ethnoarchaeological research emerged early on and grew contemporaneous with, but independent of, ethnoarchaeology in the United States. It combined studies of local “traditional” populations, historical documents, and global ethnography to interpret the archaeological record in China. As with logicist approaches, Russian and Chinese researchers have often adopted formal methodologies to identify and apply ethnographic insights to archaeological materials.

Finally, ethnoarchaeology was introduced to Latin America in the 1970s in association with archaeological research on sites in the region. Politis (2015) identifies three trends in Latin American ethnoarchaeology, including work to discover behavioral–material correlations with wide applicability, the study of cultural meanings, and research projects that integrated archaeological and ethnographic analyses to produce “indigenous histories.” One of the more recent trends draws from Spanish ethnoarchaeology and embraces a distinctly critical and post-colonial orientation in which ethnoarchaeology serves the interests and needs of local communities (Politis 2015).

Critiques of ethnoarchaeology

Throughout its history, ethnoarchaeology has faced a dizzying array of critiques. The most recent of these target processualist archetypes that emerged in the New Archaeology and then influenced ethnoarchaeological work globally, even as it began facing critiques (described above) from post-processualism (Lane 2006, 404–6; Cunningham 2009; David and Kramer 2001). Beyond these, processualists who expected middle-range theories to appear chastised ethnoarchaeology for being too eclectic when it instead generated cautionary tales. The bases for

making initial analogical ties between source and subject contexts, what are often described as boundary conditions or arguments of relevance, has been consistently problematic (Wylie 1985; David and Kramer 2001). The “stages” used in classic evolution supported racism, the adaptationist focus of the New Archaeology seemingly affirmed a scientific functionalism, while the modes of production used in Marxist theory were often dehumanizing. Ethnoarchaeology has also been challenged on ethical grounds for studying contemporary peoples to create reconstructions of ancient pasts in which they have no stake. Direct historical approaches to analogy, such as those typical of archaeological ethnographies, indigenous archaeologies, and the indigenous histories of Latin America seem more ethically sound because they make analogical ties between archaeological remains and descendant populations who are partners in the research process. However, these approaches may rely on the belief that key components of economy, social organization, or ontology have survived colonial interventions and the depredation of capitalism. American cultural history and European folk history approaches risk treating indigenous peoples and rural agrarian communities as vestigial populations resistant to change, even though they are frequently citizens of the same nation states as the archaeologists who study them. In a similar vein, post-processual archaeologies that use the standpoints of post-industrial European scholars, rather than cross-cultural insights, to investigate ancient materialities seem to overlook the important Marxian insight that subjectivity can vary depending on one’s position in a specific mode of production, raising questions about analogical relevance. Finally, the principal textbook for the subfield has also stressed that ethnoarchaeology projects rarely match the ethical, methodological, or theoretical sophistication of self-reflexive ethnography (David and Kramer 2001).

These critiques are substantial and invite a broad rethinking of analogy and ethnoarchaeology. However, the suggestion that ethnoarchaeology should simply be abandoned (e.g., Gosselain 2016) overlooks its significance to the discipline as a self-critical, consciousness-expanding exercise that is wider in its scope than any one theoretical agenda. An archaeological discipline without some form of ethnoarchaeology

does little more than reify the ideologies of its practitioners, who demographically are still dominated by middle-class men from the global north. For archaeology to legitimately produce global histories, it needs to make inferences about the past that draw from an understanding of the full diversity of the contemporary human experience. Along with other forms of critical source-side work such as feminist scholarship, post-colonialism, and indigenous archaeologies, ethnoarchaeology is fundamental to expanding on the reservoir of analogical knowledge archaeologists use to interpret the past.

SEE ALSO: Archaeology and the Present; Ethnography and Qualitative Methods in the Field; Experiment in Archaeology; Knowledge and Inference; Material Culture; Plurality and Multivocality; Positivism; Taphonomy

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Evolutionary Theories

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Evolution is the process that enables internally generated change to occur in an organization over time. Most firmly associated with changes in systems of biological organization, evolutionary theories have impacted upon three different areas of archaeological research. They have provided for an increasingly refined understanding of the development of anatomically and behaviorally modern humans alongside the histories of our nearest hominin relatives, they have informed an understanding of the processes that might have resulted in different sequences of material cultural change where those changes have been taken to represent the transmission of traditions of behavior, and they have been used to evoke a logic in the development between different scales of social organization. The first two of these areas have variously drawn upon the neo-Darwinian expression of what has been identified as the modern Darwinian synthesis, whereas the application of Darwinism to sequences of social development has been more contentious. It is therefore important that we begin by clarifying the neo-Darwinian principles that have found application in the archaeology of human and cultural evolution before considering the extent to which those principles have themselves come under review.

Darwin provided a detailed argument as to how the reproduction of life could have resulted in the diversity of living things, rather than that diversity being the unchanging product of a single design. The Darwinian model requires the operation of two relatively autonomous processes in which one, natural selection, acts upon the other, heritable variability. In this model the direction of travel of an evolving lineage is determined by the process of natural selection that winnows out the traits deemed less successful from the wider diversity that is available. Life therefore throws up possibilities, while its direction is

decided by the forces of selection. Three things should be noted. First, Darwin did not know what mechanism carried heritable traits from one generation to the next. Second, natural selection needs to act upon a range of variability within a population, and yet natural selection might appear to reduce variability over time. Third, Darwin, perhaps unwisely, adopted the aphorism of “survival of the fittest” from Herbert Spencer, thus emphasizing competition for reproductive success between individuals. This renders as problematic the evolution of altruism and those cooperative behaviors that necessarily reduced the reproductive potential of some individuals.

In 1900, the experimental results that had been achieved nearly 50 years earlier by Gregor Mendel with his controlled cross-pollinating between plants of the pea family were rediscovered. These experiments demonstrated the particulate and statistically predictable inheritance of individual traits from one generation to the next, implying that such traits were carried by some singular, determinate factor: a unit of inheritance that the Danish botanist Wilhelm Johannsen named the gene. The general synthesis of Mendelian inheritance with Darwinian evolution resulted in a distinction being drawn between the phenotype, which is the physical form of the organism upon which natural selection acts, and the genotype, being the inherited material, the survival of which is consequential upon natural selection. The resulting dominance of the gene-centered view of life was provided with an object for its analysis when, in the 1950s, Francis Crick and James Watson, drawing upon the images of X-ray crystallography that had been prepared by Rosalind Franklin, established that two intertwined polymer strands of DNA, held together by the paired bonds formed between four kinds of nucleobases, were the basic structure that carried genetic information.

The idea that genes provide a blue-print for the design of an organism is still widely accepted in the popular imagination, and by the middle of the last century it had resulted in a strongly reductionist form of neo-Darwinism. Natural selection, acting upon the reproduction of

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organisms with their relatively brief lifespans, was characterized as resulting in the ongoing and cross-generational survival of successful genetic lineages. This “gene’s eye” view of evolution was well expressed by Richard Dawkins who characterized organisms in the relatively passive role of “vehicles” that were built and that carried, and whose destiny was mainly determined by the more active genetic “replicators” (Dawkins 1976). From this perspective it seemed as if genes only existed to be replicated, while evolution traced the selective replication of successful genetic sequences. The necessary diversity upon which natural selection could act could now be provided for by the drift of new genetic material into a population and by the replication of genetic mutations, and the evolution of altruism was explained as the process of “inclusive fitness,” where the altruistic sacrifice of its reproductive potential by an individual organism was taken to increase the survival chances of the genetic replicators which that organism shared with its kin. In sexual reproduction, offspring inherit DNA from both parents, and the current ability to both map coded sequences of DNA and extract DNA from ancient material has meant that lines of transmitted biological inheritance can be traced through the long sequences of primate evolution and, to a more limited extent, across the histories of recent human populations. At the larger chronological scale this work has confirmed the evolutionary origin of modern humans (*Homo sapiens*) in Africa, demonstrated the evolutionary closeness of the relationship between *H. sapiens* and the African great apes, and clarified the biological distinction, along with some possible interbreeding, between Neanderthals and *H. sapiens*. It has also demonstrated that four populations belonging to the human genus *Homo* coexisted across Africa and Asia some 50–60 kya. Of these, only *H. sapiens* now survives. The complexity of biological inheritance is now indicated for more recent populations by the recovery of ancient DNA from skeletal remains. The matching of haplogroups demonstrates a European inheritance from south-western Asia in connection with the spread of agriculture and a northern and central European inheritance from the Eurasian Steppe associated with the development of late Neolithic single grave burial.

The Darwinian principle of evolution as a process of selective transmission, and the neo-Darwinian emphasis upon the selective transmission of genes, has been extended by the realization that other lines of heritable transmission might also submit to selection. Dawkins first raised this possibility with the idea that human life was structured by the inheritance of both biological genes and cultural “memes” (Dawkins 1976). These two lines of biological and cultural transmission provided the basis for dual inheritance theory (Richerson and Boyd 2005). If cultural inheritance is governed by the teaching and copying of behavior, where variability results from innovation and the drift of ideas and their mutation, and where selection may be due to various social demands but may otherwise be biologically neutral, then the Darwinian principle of descent with modification is still applicable to cultural systems of inheritance (Shennan 2002). As a consequence, archaeology has been able to map lineages of material cultural development as indicative of the ways various styles of cultural expression spread chronologically and geographically through human populations. Cultural evolution, with its emphasis upon the mutation and transmission of modular ideas (memes) that give rise to cultural traits, conforms to the neo-Darwinian model of evolution with its treatment of natural selection acting on particular unitary parts of the genotype (genes).

Biological evolution is witnessed by changes in a reproducing population, while populations are themselves defined through the growth and development of their individual members. Consequently, evolution should mean changes in the developmental characteristics of individuals. This explains the recent emphasis that has been placed upon the need to understand the complexity of developmental processes that affect the growth of individual organisms and that involve more than a genetic blue-print directing that individual’s development. Given that genes (or for that matter memes) do not actually do anything, the many developmental resources inherited by an individual and that extend well beyond DNA must include the contexts that enable inherited information to be acted upon. Recent moves towards a “post-Darwinian” model of evolution (Kull 1999) are therefore based upon the need to understand the evolution of developmental

systems (Oyama 2000). From the perspective of evolutionary development (sometimes referred to as “EvoDevo”), the content or meaning of an information source, such as DNA, is not contained in the material itself, but is assembled by the interpreting facilities that are contained, for example, in the cell. This approach has employed the theory of semiotics that was developed by the American philosopher C. S. Peirce (El-Hani, Queiroz, and Emmeche 2009). Peirce established semiosis as the processes in which an interpreter identifies a sign as standing for some object quality and responds as an interpretant to that identification. In biological terms, the living cell contains facilities that interpret segments of DNA as signs that specify some object of value to which the cell responds, as an interpretant, by replicating as cells that have a particular kind of function.

The treatment of life as a semiotic process (Hoffmeyer 2008) therefore questions attempts to distinguish between a biological determinism, as it has been applied to the agencies of the natural, living world, and a cultural indeterminism, as it has been applied to human agency. Instead, the processes of semiosis imply that the development of life in general can be treated as diverse processes of self-definition and self-making (Maturana and Varela 1980) that are made possible because biological systems identify and interpret available sources of information and exploit available sources of energy (metabolism) to sustain a particular niche of adaptation.

Understanding this process implies that life is, in general, conscious (Thompson 2007) and it situates the discipline of biology between the natural sciences and the humanities. Given that this is also the position that many commentators have assigned to archaeology, the implication might well be that we require a closer understanding between the two disciplines, and

where archaeology might be characterized as the historical study of human “biosocial becomings” (Ingold and Palsson 2013).

SEE ALSO: Bioarchaeology; Chromosomal DNA; DNA: Next Generation Sequencing; Genetics: Ancient; Genomics: Ancient; Material Symbols

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Experiment in Archaeology

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Academic archaeology has long suffered from an inferiority complex in comparison to subjects such as history and anthropology. Acquiring data manually by digging in the dirt is sometimes not regarded as an intellectual activity or proper academic work. In consequence, archaeology has struggled to acquire a theoretical base. Experimental archaeology did not fit into this framework at all, as it is often done by amateurs, it needs practical skills, and the knowledge of craftsmen, and is again a manual activity. Only with the material turn in the humanities and the growing theoretical recognition of making (Ingold 2013) as a fundamental part of human existence has a general theoretical framework emerged that experimental archaeology can fit into. Experimental archaeology deals with both the materials and the materiality of the past.

Of course, there are different national traditions within the discipline (Reeves and Paardekooper 2014). In Germany and many other countries in Europe, archaeology meant first and foremost antiquarian research, and the function, use, and methods of production of the excavated artifacts were not of much interest. As archaeology was part of the humanities, experiments were not part of the epistemological background of the discipline, and were relegated to a few tinkerers or to outreach work. Early experimenters were thus often not professional archaeologists. The most prominent example is the German physician Ludwig Pfeiffer, who published in the year 1913 a groundbreaking ethnoarchaeological study on Stone Age technology.

Early archaeological experiments began in the seventeenth century. These early experiments investigated whether so-called thunderbolts could have been manufactured by humans, and

whether the black coloring of cinerary urns might have been caused by smoky wood fires, that is, firing in a reducing atmosphere. In the second half of the nineteenth century, ethnographic observations were increasingly employed (see ETHNOARCHAEOLOGY), but generally as direct analogies, without any consideration of social and cultural context.

The real boom in experimental archaeology only began in the 1960s. Thor Heyerdahl's ocean crossings fired the public imagination, but there were also carefully planned long-term experiments such as the Overton Down experimental earthwork. The two books of John Coles were very important in this context, and they have been translated into numerous languages. Nonetheless, some archaeologists were very critical of the epistemological value of an experimental approach, for example, Childe, Clark, and Movius (see Shimada 2005).

From the very beginning, experimental archaeology was linked to open air museums, and the fields of ancient technology, living history, and outreach. Therefore, activities such as learning a "prehistoric craft" or "public demonstrations" in museums have been sold under the label of experimental archaeology. In a wider perspective, all these activities fit the label of *making*, but with different aims: the better understanding of the archaeological record, learning "prehistoric techniques," replicating artifacts, or teaching students and the public. Experiments, experience, and education are all important aims, but there are different methods for achieving them; therefore, a clear distinction between these different types of making is of utmost methodological importance (Reynolds 1999). The lack of this distinction has led to confusion and has been detrimental to the development of experimental archaeology as an independent and well-founded discipline.

Experimental archaeology can be defined as the use of scientific experimental methods to answer archaeological questions. This covers a spectrum from knapping a simple flint flake to complex and long-term taphonomic experiments. Söhnke Ahrens (2014) has provided

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an outstanding introduction to the subject of experiment in general. All experiments have to be replicable and take place under controlled conditions. There are numerous practical guides on how to conduct these archaeological experiments (Shimada 2005).

Peter Reynolds (1999) differentiated between:

- constructs and “reconstructions”;
- procedural and functional experiments;
- combinations of the three above;
- simulations; and
- experiments in technological innovation.

There is also a distinction between experiments in the field and in the laboratory. However, it is often impossible to clearly separate the two. In order to identify clearly defined variables that can then be investigated in systematic ways, it is often necessary to conduct numerous less well-controlled tests first. However, this is not really all that different from the procedure followed in the sciences.

In many areas of experimental archaeology, there is a broad overlap with archaeometry. Unfortunately, the latter often restricts its enquiries to composition and provenance. A very “sciency” type of experimental archaeology thus often leads to a lack of interesting research questions, especially if not enough attention has been paid to the archaeological context. However, there is a trend for a more integrated and theoretically informed archaeological science (Martínón-Torres and Killick 2014), which should lead to a more fruitful cooperation between the disciplines. This hinges, however, on the definition of clearer research questions. As Reynolds already pointed out in 1999, there is a need for a matching of research questions, methods used, and the design of the experiment.

It is also necessary to consider which questions can realistically be addressed by archaeological experiments. For example, the time spent on any specific task is mainly dependent on the experience and manual skill of the experimenter. Measuring time is only useful if the experimenter is very experienced and familiar with the workflow, tools, materials, and technologies. While the characteristics of scientific experiments have been clearly defined, archaeology cannot always

follow these prescriptions, because only very rarely can all the parameters be clearly defined. In this context, it is important to point out the importance of tacit knowledge.

The question of appropriate recording techniques is also worth consideration. An experienced smith can judge the temperature of the fire by the color of the flames, and a thermocouple may not be necessary. If a smith is unable to do this, he or she may actually not be the best person to conduct the experiment in the first place. Identifying key factors should thus precede the amassing of data of doubtful relevance. There is also the need to reflect on the specific requirements and (im)possibilities of archaeological experiments in the context of the humanities (Ahrens 2014; Wind 2001). There are numerous approaches, for example, that can be arrived at by stressing the fruitful and methodologically complementary connections to ethnoarchaeology. A better integration and a reappraisal of experimental archaeology in the context of the humanities has long been called for, and would be beneficial for archaeology in general and could lead to new research questions, beyond a limited focus on technology. Recently, the terms “dissociation from the artefact,” “intangible heritage,” “emotion,” “humanistic scholarship,” “phenomenology,” and related theoretical approaches (Petersson and Narmo 2011) have appeared in the discussion.

The methodological and theoretical basis of experimental archaeology is still poorly developed, which often leads to a simplistic positivist approach. Only a few discussions have focused on the development of a theory of experimental archaeology (Lammers-Keijsers 2005). This inherent positivism also explains why experimental archaeology thrived in the climate of processual archaeology. As yet, there are very few attempts at a postprocessual experimental archaeology, and these have mainly been in the field of phenomenology. A methodological and theoretical handbook of experimental archaeology has yet to be written.

In the end, an experiment only proves what was or was not possible. This does not, however, invalidate the approach. Experimental archaeology can be seen as a hermeneutic spiral. In a framework of a well-defined methodology and constant feedback with archaeological finds and

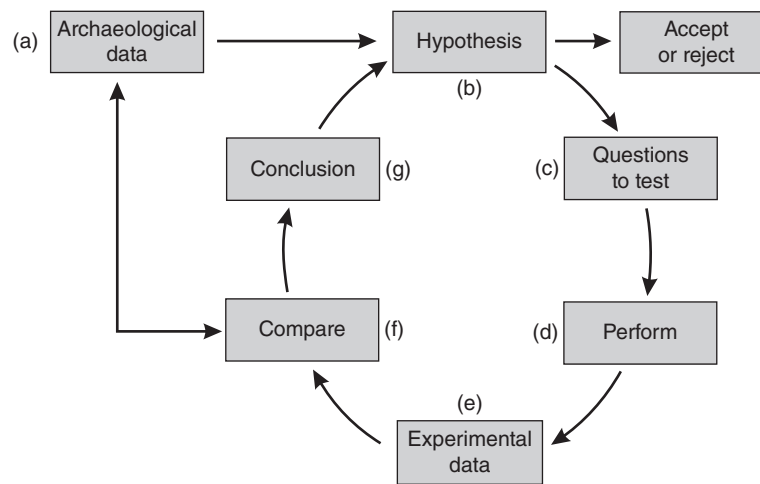


Figure 1 Circle of experimental research.

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features, historical reality can be more and more closely approximated (Figure 1).

Present-day criticism of experimental archaeology is mainly directed at badly defined research questions, lack of practical experience and technical skills on the part of the experimenters, and poorly prepared and poorly conducted experiments. Increasingly, experimenters lack the practical skills required, and it would often be sensible to publish results as test or pilot studies, rather than experiments proper. Amazingly, cooperation with skilled and experienced craftpersons is rarely sought. Many historical crafts are dying out, or becoming very rare. However, there are now some archaeotechnicians who both are skilled craftpersons and have a solid academic background in archaeology. But there is no formal education or chartered body for the subject, so any progress here depends entirely on personal initiative.

Also, the breadth of modern knowledge can be misleading. Many modern flint knappers, for example, command a much wider repertoire of techniques than was present at any point of time in prehistory. So this is also a crucial point for conducting archaeological experiments. A lack of sufficient technical support and infrastructure is holding back the development of the discipline. Suitable laboratory space is often not available. For all experiments, the analytical tools and

apparatus have to be chosen according to suitable objective and subjective criteria. In addition, the experiment has to be designed in a way that does not advantage any of the possible outcomes. Furthermore, it has to be considered how far the results have been influenced by the choice of method. Observation and interpretation have to be kept separate. By definition, all experiments have to be replicable and should be repeated several times. They can then be tested under different circumstances. This also helps the experimenter to hone his or her skills.

The results then need to be published in a correct and comprehensible fashion (<http://journal.exarc.net/eurorea-2-2005/ea/how-publish-experimental-archaeology>). Unfortunately, “failed” experiments, that is, experiments that rejected rather than supported a given theory, are rarely published, although they may have produced a good deal of information which might have helped to inform future research. In contrast, experiments that failed through lack of proper equipment or methodology are published far too often.

A critical attitude to the work that has been done is indispensable, however. A blind acceptance of received wisdom prevents the perception of truth, or, rather, the assessment of correctness. The biggest problems are still diffuse and imprecise research questions and an often

total ignorance of current and past research. In particular, a lack of linguistic skills leads to the formation of regional research traditions which totally ignore results that have been obtained in other countries. This is especially true for Anglo-American archaeology. Thus, the wheel is frequently reinvented without any progress in research methods or results.

Presently, there are two main camps in experimental archaeology. On the one hand, there are the adherents of a strictly scientific methodology (most prominent Reynolds 1999). They demand a strict separation from other subjects, such as the acquisition of practical technical experience, trying out techniques, demonstrations for the public, and living history, as well as museum education and exhibits in open air museums. Open air museums are generally understood to be excellent venues for experimental archaeology, but it is often ignored that experimental archaeology and the general public do not mix well. Therefore Peter Reynolds in his famous Butser Ancient Farm strictly separated public and experimental areas. Others claim that experimental archaeology can (or needs to) be mixed with other approaches like public archaeology, open air museums, living history, and museum education, because they are somehow fundamentally connected. Furthermore, the importance of the popularization of archaeology in terms of both politics and public expenditure is an argument that is widely supported.

These two approaches are equally valid, but a naive mixture discredits both. It may be that the time has come to find a new and overarching definition for experimental archaeology, united under the rubric of making. But it is of utmost importance to clarify preconditions and aims. Today, the number of publications on experimental archaeology and archaeological experiments is so extensive that it is almost impossible to keep track of the literature. Repositories and databases (e.g., EXARC Experimental Archaeology Collection: <http://core.tdar.org/collection/60199/exarc-experimental-archaeology-collection>) would be invaluable in accessing information about previous investigations, and planning worthwhile future work. In addition, in many countries an institutional base for experimental archaeology is lacking, as well as laboratories, university institutes, and other research institutions.

A broad spectrum of experiments has been undertaken by archaeologists. There is insufficient space to discuss them in detail here, and the reader is referred to the literature listed below. Archaeological experimentation is increasingly complex in character. While it was formerly sufficient to reproduce an artifact such as a flint dagger, nowadays the distribution and character of the debitage produced in the process will be studied, in order to understand finds distributions on archaeological sites and their subsequent transformation. The study may be taken further with an investigation of possible uses, and the resulting use wear, as well as breakage and the character of deposition. Today, the simple replication of an artifact would scarcely rate as an experiment any more.

While “making” is gaining popularity as a framework for investigation, and will hopefully become part of mainstream archaeological education, experimental archaeology is honing its definition as a distinct subfield of archaeological research, with a well-defined methodology and an ever-increasing range of techniques. Nonetheless, experimental archaeology is an invaluable method which, where it has been conducted properly, has achieved a great deal for our understanding of the past.

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Gender and Sexuality

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From its beginning as a modern discipline, archaeologists have applied the terms male and female to some persons represented in archaeological sites by skeletal remains, images, or tools used in specific activities. Serious consideration of how biological characteristics indexed by the terms male and female were linked to social identities and sexual practices, however, did not develop until the late twentieth century. Some of the impetus then came from feminist science studies (see SCIENCE AND FEMINISM). However, not all of the researchers developing this new archaeology of gender were identified as feminist. A shift in composition of the field itself took place, with many women entering the discipline undertaking research on women's roles in the past, often even as students.

Today, archaeologists exploring gender and sexuality use the same methods and evidence as other archaeologists. There is no particular form of fieldwork or laboratory work that defines archaeology of gender and sexuality. Data derived from the study of human skeletal remains, figural representation, burials, and households are common, but not the only sources employed. At the leading edge of archaeology of gender and sexuality, bioarchaeologists, trained to study human skeletal remains with archaeological questions in mind, are undertaking sophisticated research that questions the very nature of the sexes, and archaeologists drawing on queer theory interrogate the terms taken for granted in the first generations of archaeology of gender.

Historical development of archaeology of gender and sex

Sex determination, a long established archaeological approach to gender and sexuality, is an

integral part of bioarchaeology (see BIOARCHAEOLOGY; ESTIMATING SKELETAL SEX: CRANIAL AND PELVIC MORPHOLOGY; and ESTIMATING SKELETAL SEX: METRICS). Even when the production of dichotomous sexual categories is being contested, archaeologists often treat biological difference as likely to have shaped differences in lived experiences. The study of figural representations, ranging from monumental sculpture to small ceramic figurines, has as long a history of being employed in the identification of people of different genders and interpretation of their experiences. Analysis of burials has also long included the assignment of gender identity to buried individuals. Sometimes this was based on bioarchaeological analysis, but often it involved inference from materials included with the body, such as personal ornaments or tools deemed appropriate to certain activities assigned to one gender, relying on stereotypes.

These approaches long predate the late-twentieth-century development of a recognizable archaeology of gender and sexuality. Each identifies dichotomous sexes or genders through an often unreflective association with unique activities, objects, or roles. While these approaches continue in use in archaeology today, they have been challenged. Beginning in the 1960s, more theorized attention to the presumed sex and gender of specific people who shaped archaeological sites grew out of a new focus on household archaeology (Wilk and Rathje 1982).

Household archaeology occupies a distinct, if seldom acknowledged, position in the emergence of explicit archaeological research on gender and sexuality. Household archaeology was part of an agenda of systematic investigation of socioeconomic structures of settlements identified in regional scale projects. Archaeologists, sometimes explicitly drawing on cybernetic systems theory, treated regional social and economic relations as forming connections among subsystems that together produced continuation of the system, including buffering and counteracting feedback that would tend to disrupt a regional-scale system.

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Systems theory approaches to regional-scale social and economic organization did not treat aspects of human difference as in need of formal modeling, so there was no archaeology of gender in the analysis of society as system. However, these models did single out for special attention minimal units of production and consumption. This level of the system was identified with the ethnographically and historically observable household, itself a highly variable social science construct (Wilk and Rathje 1982). Household archaeology formally addressed the unpacking of households that in systems theory were treated as complex wholes not subject to analysis ("black boxes"). The original purpose of household archaeology was to understand through historical research the variability of elements in this fundamental unit of socioeconomic organization. Household archaeology relied heavily on analogical arguments justified by surveys of ethnographic and historical case studies. These analogical arguments inevitably required attention to differences along lines of age, status, and sex among the people making up households.

It is thus unsurprising that one of the most influential early contributions to an archaeology of gender started as a conference on the role of women in production (Conkey and Gero 1991). The contributions to this volume examined women's roles in face-to-face social relations from the deep time of Palaeolithic Europe to the historic Inka and Aztec states of the sixteenth century. Contributors argued that residues from food preparation, debitage from production of expedient stone tools made on the spot for specific tasks, and workshop-scale pottery crafting all needed to be examined to identify the roles of women, often previously denied or ignored. Participants proposed novel arguments giving women roles in the emergence of plant cultivation, the social organization of nonstate societies, and transformations in the economic systems of states undergoing colonization.

Initially, archaeology of gender was practiced comfortably within dominant positivist research approaches. With the emergence of archaeology of gender as a specialization in the 1980s and 1990s, marked by numerous conferences, edited volumes, and even entire journals, it became evident that archaeologists were not necessarily

employing unified definitions of terms, or exploring agreed upon research questions. Some work was oriented to create a larger body of data about the historical position and actions of women: an archaeology of women. Other work was aimed at defining theories of gender as an aspect of historical social, political, and economic relations, often informed by contemporary feminist thought from outside archaeology (see *SCIENCE AND FEMINISM*): feminist archaeology. Less common was work directed at interrogating the assumptions that archaeologists used when thinking about the past, and identifying places where assumptions about gender were embedded in normative archaeology: what we could call an archaeology of gender.

Today, a spectrum of research positions exists in archaeology of gender and sexuality, from perspectives inspired by queer theory that question the use of any categories of sex or gender, to continued reliance on biological markers used to create dichotomous male and female categories taken as fundamental to binary social gender relations. Where archaeologists engage with feminist science studies (see *SCIENCE AND FEMINISM*), they contribute to discussion of the multiplicity of sexual categories that can be based on different biological markers. When archaeologists draw on work in gender and women's studies, they argue that social identities must be viewed as intersections of different aspects of individual experience, requiring consideration of racial, ethnic, and socioeconomic status along with sex or gender. Those archaeologists who build on insights from queer theory see archaeology as a source of evidence that sex or gender categories are not natural outcomes of biology, but rather are products of specific culture histories.

The most promising contemporary research goes beyond identification of women or even of people of multiple genders in specific past situations. Bioarchaeologists have taken leading roles in questioning the effects of dividing human populations into two subgroups for analysis (see *BIOARCHAEOLOGY; ESTIMATING SKELETAL SEX: CRANIAL AND PELVIC MORPHOLOGY*; and *ESTIMATING SKELETAL SEX: METRICS*). Archaeologists drawing on queer theory have begun to employ the rich reservoir of case studies assembled through positivist research to show

how archaeology of gender and sexuality contributes to broader projects of denaturalizing the representation of specific forms of human social organization as inherent aspects of human existence (Geller 2009; Ghisleni, Jordan, and Fiocoprile 2016; Weismantel 2013). Contemporary approaches make archaeology of gender and sexuality relevant to broader social sciences and even social policy.

From an archaeology of women to archaeology of gender and sexuality

Documentation of women in prehistory was the first product of archaeology of gender as it emerged in the 1980s. New studies often used recent ethnographic observations, or even undertook new ethnographic research to expand the basis for answering such questions as to who hunted, who butchered, who prepared and tended fields or raised animals. Researchers proposed that women had greater roles in making the tools used in everyday life, and in domesticating plants and animals, than traditionally assumed.

A subgroup of studies of women in the past pursued the identification of women in positions of power, previously overlooked or explained as exceptional. Some studies drew on less well known historical traditions, for example, power possible in contexts open only to women, like celibate communities of nuns (Gilchrist 1994). Others reconsidered the minimization of women's power in societies where some historical women had long been recognized but interpreted as subordinated by men of the ruling class, an approach taken to the Classic Maya by an international group of researchers, many explicitly feminist (Joyce 2001).

While sometimes derisively characterized as "add women and stir" research, this work, whether explicitly or not, involved a theoretical shift from previous archaeological practice. In place of a singular, normative human subject (by default male), archaeologists had to specify the social position of the actors whose traces they were interpreting.

There were, however, problems with the simple approach to looking for women in the past (Joyce 2008). These are exemplified by proposals

like those that women had major roles in the initiation of plant domestication and the creation of the first fired clay vessels. Arguments like these usually proceeded from the assumption that women in the past would have been responsible for domestic tasks, such as preparation of meals and tending of fires, giving them a closer relationship to the plants and materials altered in significant moments of technological change. This assumption can be recognized as a kind of strategic essentialism, countering a tendency to obscure women's undeniable presence in the past by demanding some kind of special "signature," a unique artifactual pattern in an assemblage that would be signifying the sex of the person making or using it. Strategic essentialism stabilizes cultural interpretation long enough to allow proposals that a subordinated or obscured person was active, at the price of subscribing to a generic form of identification. Yet generic forms of identity employed in strategic essentialisms are often held to be resistant to change, or even natural and in-born, raising a new set of problems.

The essentialism at work in archaeology of gender was often supported by a historical argument: that human societies have always had a division of labor based on sex in which women's roles were partly determined by reproductive biology. Archaeologists dealing with the long history of human evolution argued that due to differential demands of pregnancy and infant care, and the inability of males to know that they are genetically related to the children born to women, humans would have had a long evolutionary history of female childcare, including the first provision of food to others. This argument relied on a close linkage between a biological sex and social gender role that can be seen in retrospect as unfortunately reductive, since it left no role for the unpaired female (or male), or the female without offspring, and positioned forms of sexuality that were not male–female pairs as abnormal or unnatural.

It was issues like these that led archaeologists to begin to question basic assumptions about gender, producing a critical archaeology of gender. Archaeologists working in societies with a high degree of socioeconomic variation, especially those informed by Marxist analysis, suggested that gender needed to be understood in articulation with socioeconomic status. For

these archaeologists, the archaeology of queens was less about gender, and more about class structure and power.

Archaeologists inspired by the work of queer theorists, especially Judith Butler, questioned the proposition that biological sex was the ground for the development of social gender. Butler, and archaeologists employing related analyses, saw the separation of sex and gender in discourse as misleading, producing an effect of naturalness around what they argued was always a social experience of being. The corporeal aspects of being that archaeologists called sex were not precultural, and they did not provide solid grounding on which cultural performances that could be called gender could be formulated (Joyce 2001). For these scholars, it did not matter if archaeologists acknowledged that there was no deterministic correspondence of sex and gender, no universal female experience. The flaw was already there in treating sex and gender as two different things, one more fundamental than the other.

An important body of archaeological work built on questioning the sex/gender equation by examining the existence of multiple or alternative ("third") genders. Inspired by ethnographic and historical sources, archaeologists working in the Americas in particular noted that descendant communities of the societies whose remains archaeologists explored often recognized three or more social genders (Joyce 2008). Less commonly, archaeologists drew on work by feminist biologists arguing that even biological sex was not a dichotomy, whether it was assessed based on chromosomes or reproductive organs (Geller 2009).

The way discourses and practices of sex and gender formed became the focus of many archaeologists who followed this critical path. Nothing could be taken as natural anymore. Archaeologists investigating sex or gender relations (now often interchangeable, or even used as a compound term sex/gender) needed to account for the social and economic organization through which categories of persons could have emerged in the past in action or performance, or as objects of social constraints or freedoms. Historical archaeologists, working in situations where legible documentary records are one of the bodies of material available, were central

to the development of critical approaches to an archaeology of gender (e.g., Gilchrist 1994). Yet archaeologists working on even very early societies for which forms of data are less rich also were able to undertake analyses that asked how genders manifest or become recognizable, and what forms gendered social relations might have taken, without presuming the presence of a simple dichotomy between male and female linked to bodily differences.

At the same time that analyses of the social determination of gender developed out of critical archaeologies of gender, other archaeologists continued to be concerned with how the experiences of people are shaped by whatever sex or gender relations exist in specific historical circumstances, with special attention to the material dimensions of experience that provide the focus of archaeological methods and arguments. This focus on experience often involved consideration of embodiment separate from gender (see *BODIES AND EMBODIMENT* and *EMBODIMENT*). In the late 1990s, it gave rise to novel work that went beyond the parameters of archaeologies of sex or gender to consider sexuality (Schmidt and Voss 2000). The archaeologists who engaged with questions of sexuality might share an interest in social regulation with archaeologists of sex or gender, but they also were concerned with experiences of desire and sexual practices. Rather than simply cataloguing additional genders, they asked what kinds of sexual relations were practiced where genders beyond male and female were recognized. Ultimately, archaeology of sexuality opened up the field to queer theory, which continues to be a major source of advances in the archaeology of gender and sexuality today.

Current emphases and future directions

Archaeology of gender continues to include much work based on the assumption that there is a biological dichotomy of male and female which different societies recognized with different genders, sometimes more than two. This work continues to add empirical case studies of women's and men's roles in past societies. Contemporary archaeology of gender and

sexuality grounded in queer theory goes further, and includes work intended to disrupt any such assumptions. Researches engaging with queer theory note that most archaeology continues to be implicitly heteronormative, assuming that in all past societies the majority of people were engaged in male–female sexual relations (Geller 2009; Joyce 2008; Weismantel 2013). Even research that seeks to trouble archaeology’s heteronormativity can sometimes be limited to consideration of “alternative” sexual cultures, which may leave in place the assumption of heteronormativity.

The contradiction between archaeological work based on assuming a determinative relation between biological sex and social gender, and critical work rooted in queer theory that rejects the use of such terms as universals, can lead to exchanges in which archaeologists on one side assert that dichotomous sex/gender systems are natural (and thus universal) because they are “necessary” for reproduction, and those on the other side argue that biologies are always recognized in terms of social categories of what is taken as natural (and thus acceptable). Contemporary work, however, goes beyond these “binary binds” (Ghisleni, Jordan, and Fiocoprile 2016). In contemporary archaeology of gender, gender or sex is treated as historically contingent, as likely to be fluid as fixed. Contemporary work may treat sex or gender as a spectrum, not seeking to identify any specific number of genders or sexes.

This does not result in inattention to ways human difference has been mobilized in unequal relations of power, or a lack of attention to recognizing people in the past who might have systematically been denied access to power due to their sex or gender. While maintaining connections between bodily experience, difference, and sex and gender, contemporary work has moved away from the centrality of reproduction that

characterized earlier archaeology. Biological sex and gender are no longer taken as universally central to human identity. Even when they are recognizably important, biological difference or cultural experiences that archaeologists recognize as sex, gender, or sex/gender are now routinely examined in terms of the intersection of race, ethnicity, age, and social status.

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History and Sociology of Science

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Archaeology and sciences or archaeology as science?

From the late nineteenth to the early twentieth century, human and natural sciences were gradually reorganized into institutionalized forms. The diversification of research trends in archaeology, a trend also observed in other sciences, led to a number of ways to refer to the natural sciences, which ranged from using them as a model of scientificity to defining the difference between them and the human sciences. Local histories of scientific institutions, research traditions, and political and personal choices alike influenced the position of archaeology within the scientific field—a position that could be closer to or more distant from the human and natural sciences. The case of prehistoric archaeology highlights this crossing over of branches in the classification of sciences. The development of prehistory as a scientific practice in the second half of the nineteenth century relied on a wide range of approaches, including ethnography, history, physical anthropology, paleontology, geology, and botany, from which prehistory borrowed methodological and conceptual tools. In the nineteenth century, archaeology (see *ARCHAEOLOGY*) and prehistoric archaeology were part of a large research field that encompassed geography, physical anthropology, linguistics, and ethnography and aimed to describe and understand human history from natural and cultural perspectives (Blanckaert 2000). Consequently there is an intrinsic relationship between *archaeology* and *science*: the aim of producing archaeological

knowledge is *in itself* a scientific project, and it is preferable to talk about the relationships between archaeology and other sciences.

The term “archaeosciences” is loaded with the same content: if a part of archaeological practice is scientific (the “archaeosciences”; see *ARCHAEOLOGICAL SCIENCES*), what about the other part? The role of historians and sociologists of science is not to find the best solution to this problem, but rather to investigate the variations in the definitions of these terms. An important issue is to identify the relationship (in terms of epistemic and social dimensions) between archaeological practices and practices in the sciences applied to archaeology—in other words, to explore the diachronic and synchronic variations in the ways archaeology has been grounded as a scientific enterprise and the controversies surrounding this topic. Indeed, the concept of archaeoscience has its own history and is closely related to the concept of archaeometry (see *ARCHAEOMETRY*).

A brief examination of the evolution of the latter can clarify the relationship between archaeology and other sciences. It is important to understand the meaning of *-metry* in archaeometry. The term started to become popular in the 1960s, and in 1961 the first “Symposium on Archaeometry” was held in London; it was an annual meeting that focused on the applications of physical science in archaeology. The growth of archaeometry increased rapidly in the mid-1970s. From 1975 onward, the location of the symposium changed every year; the symposium itself became international and renamed “International Symposium on Archaeometry and Archaeological Prospection.” This internationalization was also reflected in the creation of the *PACT* group in 1976, by the Council of Europe. This group was defined as a European study group dedicated to the study of physical, chemical, biological, and mathematical techniques applied to archaeology. From 1977 on, this group published its own journal, the eponymous *PACT*; at the same time, in 1976 the *Groupe des méthodes physiques et chimiques de l'archéologie* (GMPCA) was founded in France in 1976 and started issuing its own journal,

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Revue d'archéométrie, one year later. These three cases illustrate different definitions of archaeometry: in the UK symposia and in the French GMPCA, mathematics was included only insofar as it provided methods to process the results of physical and chemical measurements; on the contrary, in the European PACT group, mathematics was an integral part of the group's definition.

The concept of measurement is relevant to the measurement of abstract properties in mathematical objects and of concrete properties in physical objects. From the 1970s onward, however, archaeometry was concerned mainly with the measurement of concrete properties; it excluded mathematics and restricted itself to physical and chemical procedures designed to investigate archaeological facts. This evolution was also related to the professionalization of archaeology, the growth of archaeometry as a specialized field, and the redefinition of the relationships between archaeologists, mathematicians, physicists, and chemists. The extensive scope and multidisciplinary nature of archaeometry and of the archaeosciences illustrate the inadequacy of an analysis based only on a normative classification of the sciences and the relevance of a sociohistorical inquiry on this issue.

The first section of this entry focuses on the different approaches taken by authors who assess the relationship between archaeology and other sciences from social and historical perspectives, and on the evolution of these approaches. The evolution of these authors' aims is also examined. The second section focuses on a long-term perspective. Since the nineteenth century, archaeological research has integrated a range of aims, facts, and procedures borrowed from or shared with other scientific disciplines.

Scientific transfers and applications in archaeology: an overview of social and historical approaches

During the twentieth and twenty-first centuries, the position that authors occupied in their discipline and the nature of their work on the history of the relationship between archaeology and other sciences can be classified into three main categories. A first group is formed by internalists:

archaeologists who construct the history of their own discipline and practices, and aim to advance archaeological knowledge. The second group is formed by archaeologists who are concerned with the history of their discipline as a social practice (see *SCIENTIFIC PRACTICE*). The third group consists of externalists: historical and sociological analyses of the relationships between archaeology and other sciences are produced by historians, sociologists, or ethnologists positioned outside the field of archaeology. They aim to advance the knowledge of general phenomena related to past and present activities based on the case of archaeology.

Progress in archaeology: archaeology's relationships with other sciences

From the first decades of the twentieth century to the present day, many archaeologists have published reviews or methodological textbooks that aim to describe the diversity of tools available from the natural and formal sciences, as well as their limitations in archaeology. These contributions, assessing the relationship between archaeology and other sciences, aimed to strengthen the archaeological discipline and to support the research of archaeologists. In addition, they were conceived as a means of exposing the progress of the discipline, since they coincided with the first attempts at professionalizing prehistory (in the 1920s) and with the development of technical tools in physics, chemistry (see *CHEMISTRY IN ARCHAEOLOGY*), and isotope (see *ISOTOPES*) research (in the 1950s). An emblematic contribution is Annette Laming's book *The Discovery of the Past: Recent Progress and Techniques in Prehistory and Archaeology* (published in French; see Laming-Emperaire 1952).

Archaeologists examining their discipline as sociologists or historians

Since the 1990s, the relationship between archaeology and other sciences has been investigated by archaeologists influenced by or aware of approaches developed in cultural and social history and in the history of science. Examining the institutions, the actors, and their practices, these authors have tackled the relationship between

archaeology and other sciences within the context of formation and development of archaeology as a scientific discipline (Hurel and Coye 2011; Kaeser 2011). More recently, this relationship has been approached from the point of view of the development of specific tools and methods (e.g., 14C dating, dendrochronology, fluorine) that involve archaeology and natural and formal sciences, in a context of strong disciplinary affirmation (Delley 2015). Such researches focus on the behavior of the scientists and assess their actions in complex social interactions (e.g., power relations between disciplines and institutions, the role of politics in science, the relation between science and the army, medicine, culture). The use of archives, the contextualization of observations, as well as the historicization of the categories commonly used in archaeology (e.g., dating, modernity, interdisciplinarity, amateur, professional: Plutniak 2017) are constitutive of this approach, which is recognized either as a component of archaeology or as a part of the history of science.

Archaeology as a case study for social studies of science

Since the 1940s and following the pioneering work of Robert Merton, social and historical studies of science grew in number and were empirical investigations of various disciplines. Until the present day, however, archaeology has rarely been investigated by sociologists or science historians. In fact, social studies of sciences have focused mainly on natural, formal, and experimental sciences; one explanation is that archaeology is a newer discipline by comparison to physics, mathematics, or physiology. Nevertheless, there are some studies that have addressed sociological questions regarding the relationship between archaeology and other sciences. An example is the sociology of expertise developed in Bessy, Chateauraynaud, and Lagrange (1993). This work investigates the case of Glozel, an alleged forgery site, and shows how arguments grounded on the use of radiocarbon (see RADIOCARBON CALIBRATION AND AGE ESTIMATION) and thermoluminescence (see DATING CERAMICS AND LUMINESCENCE) can be controversial. The sociolinguistic approach

is another example (Goodwin 2000). Dealing with ethnomethodological questions related to the role of vision (or visual experience) in the analysis of situated practices, Goodwin analyzed how archaeologists decide the description and colors of a stratigraphy. During the 1990s, the influence of postprocessual archaeology and its particular relation to ethnography and reflexivity (see SYMMETRICAL ARCHAEOLOGY) blurred the frontier between archaeologists analyzing their own discipline and sociologists or historians examining archaeology as a case study. An example is the collective book on the ethnography of archaeology (see ETHNOGRAPHY AND QUALITATIVE METHODS IN THE FIELD) edited by Edgeworth, an archaeologist, which collects papers from archaeologists, sociologists, curators and linguists (Edgeworth 2006).

The relationships between archaeology and other sciences: examining time

The relationship between archaeology and other sciences encompasses a wide range of scientific practices and relationship modes, for example transfer of concepts (by analogy or metaphor), methods (devices or skills), or knowledge aims. To give a short but broad example, this section focuses on the case of examining time (see TIME AND TEMPORALITY) by distinguishing three main categories of scientific methods of inquiry: observing (the effects of time), measuring (the effects of time), and computing (temporal data).

Observing the effects of time

Since the second half of the nineteenth century, observing the effect of time has been a central question in prehistory. Archaeologists expected the natural and formal sciences to devise methods to resolve this issue, in addition to the usual tools of classification (see ARCHAEOLOGICAL CLASSIFICATION) of artifacts and stratigraphy. In the early nineteenth century, the paleontologist Georges Cuvier and the mineralogist Alexandre Brongniart defined a methodological tool where faunal characterizations were used to establish

a relative chronology between different stratigraphical layers. A few decades later, a scheme for recognizing and characterizing the successive stages of the development of material culture was established by Christian Jürgensen Thomsen and Jens Jakob Asmussen Worsaae on the basis of the collections stored at the National Museum of Copenhagen. Named the “three-age system,” this conceptual tool relies on the morphological and technological analysis of archaeological material. The composition of this material (stone, bronze, or iron) establishes a division of time. In the 1840s the demonstration of the antiquity of “man” by Jacques Boucher de Perthes was built on naturalist and cultural principles involving paleontological, geological, anthropological, and cultural observations (see MATERIAL CULTURE) and established the first elements of what would become the scientific practice called prehistory. At the same time, in Denmark, a commission of experts composed of archaeologists and naturalists explored the famous kitchen midden (*kjoekkenmoedding*), whose chronological attribution was highly problematic. Around the 1870s, Gabriel de Mortillet used in his classification of prehistoric industries paleontological stratigraphy and the “three-age system.” Naturalist and cultural conceptions are built using evolution theory, which is based on geological and paleontological evidence applied to the morphological classification of human artifacts (Hurel and Coye 2011).

Since the late nineteenth century, wetland zones—marshes, bogs, and lakeshores where organic remains are particularly well preserved—have been locations of intense exchanges between naturalists and archaeologists. During the first half of the twentieth century, these collaborations took institutionalized forms with the creation of laboratories and institutes in Tübingen, Groningen, and Basel that aimed at including botany and palynology—besides sedimentology, paleontology, and material culture—in the practice of archaeology. The history of vegetation and climate (see CLIMATE CHANGE AND DATING), combined with the fine analysis of stratigraphies and artifact typologies, stems from the same preoccupation of observing the effect of time from a natural and cultural perspective.

Measuring the effects of time

The introduction of measurement in archaeology was an important methodological and epistemological step (see MEASUREMENT THEORY); furthermore, it also divided actors according to whether they could perform the method in question or not. These measurements concerned mainly the properties of cultural artifacts and organic and physical facts to the extent that they could reveal the effects of time.

A first case is the measurement of cultural assemblage properties. An example is the early development in seriation (see SERIATION) methods, introduced by Flinders Petrie in the late nineteenth century. Petrie also authored one of the first extensive applications of mathematics to archaeological facts in his book *Inductive Metrology*, published in 1877. Seriation methods consider a set of objects and measure the properties of each (for instance types of potteries). The variations observed in the targeted set lead the observer to infer the relative chronology of these objects. American archaeologists largely adopted and improved statistic-based seriation methods (see DESCRIPTIVE STATISTICS), notably in the work done in the 1910s in the Pueblo and Zuni regions by researchers such as Alfred Kidder, Alfred Louis Kroeber, and Clark Wissler, who integrated these methods within an evolutionary (see EVOLUTIONARY THEORIES) framework (see Lyman and O’Brien 2006).

Dendrochronology, which was introduced into Europe by Ebba Hult de Geer and Bruno Huber during the 1930s and 1940s, in botany (see CHARCOAL AND WOOD ANALYSIS), is at the frontier of observing the effect of time and measuring it. Dendrochronological curves can be built, and thus historical sites dated, by comparing and correlating the patterns of tree rings. The use of this method in dating prehistoric settlements was limited to establishing (although very precisely) relative chronologies until the 1980s.

Since the 1950s, radiocarbon dating has been considered, in textbooks on method, the emblematic example of a collaboration between archaeology and other sciences. This tool, developed shortly after World War II, determines the age of an object by measuring its radioactive decay. Analyses are performed in physical laboratories disconnected from the archaeological milieu. In

addition, the tool was quickly presented as being “under control” by laboratories, which expected a direct correlation between the ^{14}C decay curve and the calendar time curve. This assumption relied on the false hypothesis that the production of ^{14}C was constant through time. Statistical and computational methods of calibration (see RADIOCARBON CALIBRATION AND AGE ESTIMATION) were developed to solve this problem of the fluctuating ^{14}C production in the atmosphere.

Time computation

During the second half of the twentieth century electronic computers became more powerful. This advancement led to redefinitions of previous methods: the research problems might have been the same, but the methods used to solve them radically changed, as computational complexity became less of a limitation (see COMPUTER APPLICATIONS IN ARCHAEOLOGY). The main difference was that calculations were not made on the observed properties of archaeological facts, but directly on calendar data integrated into an abstract statistical time model. A shift occurred from dealing with representations of temporal effects to dealing with representations of time, which allowed for the integration of multiple dating sources in the same formal framework.

Regarding the development of dendrochronology in Europe, where climatic signals are weaker than in southwest America (where the tool was first developed by Andrew Ellicott Douglass), local dendrochronological curves can be inserted in a long referential curve, which connects the present day to prehistoric times and provides archaeologists with an absolute dating tool that necessitates the use of statistic computations. Physicians and statisticians developed Bayesian (see BAYESIAN STATISTICS) frameworks that allowed the calibration of unique datings and the integration and correlation of multiple dating sources (radiocarbon, dendrochronology, thermoluminescence). From the 1970s on, an important chronometer was developed on the basis of ancient DNA (see GENETICS: ANCIENT and GENOMICS: ANCIENT) and of the known mutation rate of biological molecules. The “molecular clock” hypothesis and method offered

a new way to estimate time in archaeology. Both DNA sequencing (see DNA: NEXT GENERATION SEQUENCING) and the calibration of the relative duration provided by the molecular clock rely on computational techniques.

In fact, the difference between observing and measuring the effects of time on the one hand and analyzing temporal data on the other is not only a matter of methods or concepts. The introduction of new methods to investigate time in archaeology also redesigned the organization and practices of archaeology, modified its boundaries, defined new powers and relationships between archaeologists and specialists in other disciplines, and changed the image of archaeology in society. Archaeosciences and archaeometry have for instance connected archaeology with the iconic place of modern science: the laboratory (Delley 2015). These aspects are empirically investigated by social scientists and historians.

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Human Lives and Deaths

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Positioning the problem of a transdisciplinary archaeology

Archaeology provides multiple pathways from fragmented remains to reconstructed human lives and deaths in the past. These pathways require not only sound empirical grounding and archaeological evidence, but also archaeological and social theory broadly defined, thus tying together the natural sciences, the social sciences, and the humanities. The combination of solid data, sophisticated methods, and informed theoretical interpretation has driven our insights into past lives forward toward new insights and questions over recent decades. The current rise of scientific archaeology has in many ways contributed to increasing cross-pollination within the field, and to some degree dismantled the intradisciplinary conflict that arguably characterized archaeology in the 1990s. But as archaeologists become increasingly specialized, we must remain vigilant to not undermine this growing transdisciplinarity. To avoid a rift between the natural sciences, the social sciences, and the humanities within archaeology, it is imperative that we not only use each other's results, but also continue to build the cross-disciplinary literacy and connections, as new approaches, methods, and paradigms develop in these different areas.

By using the archaeology focused on death and mortuary practices as an example, this entry outlines the potential of a rich transdisciplinary archaeology, and some of the challenges archaeology faces in fully integrating its different epistemologies. The archaeology dedicated to studying burials and the remains of the dead is an example both of the complexities of archaeological inquiry, drawing on multiple lines of evidence and approaches, and of the potential wealth of information about human lives and deaths in the past. Here, we can study

the remains of the human beings themselves to infer biological and environmental dimensions of identity, including age, sex, health, diet, migration history, and genetic make-up. But mortuary remains are also the material traces of ritual and social practices, which—if documented, visualized, and analyzed with carefully theoretically informed methodologies—can reveal equally significant knowledge about the past, opening up to insights into cultural and social identity, lived experience, social relationships, power, ontology, and the practices that framed the understanding of death among the participants. This work draws more explicitly on the humanities and different kinds of social theory. But as we see strides forward fueled by synergies between scientific methodologies and theoretical approaches, we also see tensions within the field that, if left unquestioned, may grow over the coming years. Archaeological science has made very significant headway in the past decade in ways that immediately engage mortuary archaeology. The rise of “forensic anthropology,” ancient DNA research, stable isotope analysis, and so on has undoubtedly enriched an archaeology that long remained distanced from the potentials of these approaches, relying more heavily on humanities and social theory analysis, missing out on the generation of data that would improve the pathways toward a more multifaceted engagement with traces of the past. With more widespread archaeological use of—and argumentation with—scientific data, it seems that the relevant question is, can the pendulum swing too far? The disciplinary shift has created a situation where new data are generated at a high pace, both because methods have improved and become increasingly accessible to more researchers, and because this archaeology is highly fundable, being so seemingly more concrete in its output of “facts.” Is there a risk that archaeology in this new situation is turning away from problematizing its humanities and social science side, the way some post-processual archaeology in the 1990s turned its back on science? As we witness this surge in data generation, and in scientific competence within archaeology, it is imperative that we also push to integrate

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these data with research questions and theoretical frameworks that recognize the complexity of the past in a transdisciplinary way, to protect the complex, rich scholarly value of the discipline.

Pride, prejudice, and power

Contemporary archaeology is still struggling with internal misunderstanding, where the different sides hold reductionist views of one another based on subdisciplinary pride and prejudice. Natural-science-based archaeology often looks at the archaeology anchored in humanities and social theory as too interpretative, as lacking in empirical grounding, and sometimes as too obscure—unnecessarily complicating matters with impenetrable jargon. Similarly, while the humanities-oriented archaeology may yearn for detailed laboratory results, there is a tendency to view the archaeological sciences that produce these as positivist and rigid, not able to theorize, nuance, and problematize in relevant ways. Both these positions are unfair and unproductive. In the case of mortuary archaeology, the scientific analysis of human remains allows assays that can reveal previously inaccessible information about a range of issues including diet, migration, and genetics. These new data undeniably feed into our knowledge about the past and invite us to ask questions relevant to the humanities-driven archaeology. Similarly, these data are enriched by a deep and nuanced understanding of the archaeological contexts and research history, and of how human societies work, something we access through social sciences and humanities. As Lidén and Eriksson (2013) point out, good scientific inquiry is driven by research questions, dependent in turn on transdisciplinary theoretical frameworks. To this we can add that good humanities-driven archaeology is always grounded in archaeological data and evidence. Undoubtedly, the different paradigms rely on each other. I explicitly avoid using terms like “interpretative archaeology” and “theoretical archaeology” here, since they implicitly rely on the false assumption that scientific archaeology is not interpretative or theoretical. A true transdisciplinary archaeology recognizes that all archaeology is methodological, theoretical, and

interpretative, and that it is by integrating the complexities offered by the “other side” into one’s own process of analysis and interpretation that our insights will benefit.

To bridge the rift, we need to recognize the mutual dependency and further develop a literacy across the subdisciplines, allowing us to connect and evaluate the arguments. We also need to foster a more collegial culture in how our results are published and communicated. New detailed information and observations gained from bioarchaeology and novel laboratory methods—from “big data”-driven ancient DNA analysis to mass spectrometry and innovative forms of digital imaging and statistical analysis—have all added to what more traditional archaeological and biological anthropological observations have achieved in the past. Innovative scientific methods allow us to expand our inferences about human societies and populations, about chronology and environment. While the value of these results is undeniable, the ways in which they are presented can actually undermine transdisciplinary dialogue. This is the case when laboratory-driven projects produce reproducible, potentially highly reliable results, yet they are motivated basically by falsifying straw-man hypotheses that only represent a fragment of the scientific work done by previous generations of archaeologists, working with more traditional methods (e.g., lithic or ceramic typology, stratigraphy, settlement structure and patterns). In fitting readily into “It-has-now-been-proven-that” headlines, laboratory-driven research’s big data can come to completely overshadow earlier archaeological support for the hypothesis claimed now to have been so strongly favored. It is good scientific practice in any field to recognize previous research. As archaeologists working across subdisciplinary boundaries, we need to learn how to implement cross-disciplinarity in a way that acknowledges this particular nature of our work. As an example, an ancient DNA analysis looking into the process of neolithization in Europe must not only recognize the relevant research in methodology, population history, and genetics, but also consider in depth independent lines of archaeological evidence for contact, migration, sedentism, domestication, demographic intensification, social inequality, craft specialization, ritual, ontological changes,

and so on. Expecting and encouraging this kind of familiarity would stimulate archaeological research teams to become more diverse, foster a deeper competence in the field, and yield more interesting interpretations, questions, and even methodological innovations.

Similarly, the critics of archaeological science must develop a more generous attitude to the value of the data that are currently produced. At first glance, the results of a study that has sequenced the genome of a single individual (for example, to account for eye and hair pigmentation) may seem trivial to an archaeologist used to working with the larger “big questions” in the field (for example, neolithization) or on broad but critical research questions seeking to problematize identity, gender, and power within communities. But even this collection of presumed trivialities must be viewed through the lens of basic or foundational research, which is, and must be, regarded as valuable in itself. As in other sciences, data revealed from archaeological sources can initially seem trivial, but may eventually become an essential part of a foundation that allows us to gain a better and more nuanced insight into the past. The information about eye and skin color in an individual (e.g., Allentoft et al. 2014) becomes significant the moment we use it to discuss adaptation and gene flow at a demographic level, but also aspects of human life in the past, such as beauty standards, human relationships, identities, and cultural encounters. Similarly, the detailed reconstructions of the handling of the dead body gleaned from the analysis of micro-movements of bones during the process of decomposition in archaeoethnology (Duday 2009) gain their significance as we start to ask questions about why people treated their dead in specific ways (Nilsson Stutz 2003). Even as an isolated observation, such detailed work in mortuary taphonomy feeds our shared scientific understanding of decomposition processes that may become more broadly useful in future research. Natural science approaches thus recognize the value of methodologically reproducible evidence gathering and hypothesis testing, in ways that humanities-oriented research does not, thus supporting value in foundational knowledge building. Critical self-examination and mutual understanding alike are necessary on both sides to reduce the sciences–humanities divide.

Building bridges and looking for the feedback loop

While basic or foundational archaeological science research into skeletal biology, population genetics, or isotope chemistry, and so on is valuable in itself, it becomes *archaeology* when it is framed within a search for insights into human life and death in the recent or distant past. To paraphrase Lidén and Eriksson (2013), it is all about the questions we ask. To accomplish this, a combination of data, scientific analysis, and philosophical and critical social theory is necessary. Methodologically driven empirical approaches in bioarchaeology and forensic science often provide a foundation for scientific studies within a range of fields including burial taphonomy (Duday 2009; Nilsson Stutz 2003), disability (Hubert 2000), illness (Martin and Osterholtz 2016), and mortality and violence (Martin, Harrod, and Pérez 2012). These observations are then subsequently enriched in humanistic inquiry about lived experience and for general theoretical argument about bodily affect, identity, and power, for example. The inquiry ideally works in a feedback loop, allowing all engaged fields to enrich our perspectives on the past. While it is impossible here to give a complete account, I will limit this presentation to a few examples of areas of research where a combination of scientific and humanistic perspectives clearly enriches our insights into the lives and deaths of the people we study and ultimately improves the research quality in all fields.

When looking at a parameter like identity, we soon discover the gains from this type of bridge building. While the term “identity” in archaeology has been problematized and nuanced by the humanities and social sciences (Fowler 2004), it undoubtedly relies on scientific archaeology *as well*. While we can problematize cultural and social age and gender and explore the many ways in which these are affected by, and in turn also affect, culture and social realities, the analysis requires a connection, even when problematized, to biological age and sex. Questions of social class are elucidated and nuanced not only by the material culture associated to the human remains, but also by the macro- and microscopic traces of pathology, nutrition, health status, and so on revealed in scientific analysis. Beyond sex,

age, and social class, we know that health and disability can be fundamental factors in identity production, and these are identified and partially understood through paleopathological analysis. But then, of course, this scientific data must be generated by asking questions that are relevant for the context—insights that can only be achieved through a deep knowledge about the archaeological period and about how human societies work. Even at the level of sampling for isotopes and DNA, the scientist relies on archaeological knowledge about the period (social structure, mortuary practices, contacts, technologies, subsistence, etc.), and more fundamental anthropological and philosophical understanding of how cultures work, to shape their research design. After the analysis, the results must be weighed with this deeper understanding in mind to become archaeology. What, for example, does a nutrition deficiency or a disability mean for an individual within this society? How may these phenomena be noticed and understood within the society? Did people have access to care? Were some pathologies social stigma, or were they actually social assets (e.g., Porr and Alt 2006)? These questions, in turn will be enriched also by the scientific understanding of the effects of food insecurity, disability, and aging. As we proceed to this level we enter a realm of archaeology where we rise above the data and fundamental models, and get to the level of biocultural human lives and deaths. We can elucidate a lived experience of migration that leaves its traces in the isotopic make-up of our bones, of diet, illness, wealth, and poverty. Identity becomes multidimensional and dynamic and can no longer be dissociated from cultural practices and experience, and in turn allows us to connect these multidimensional concepts to others, like food production, health, prestige, power, and economy. Similarly, violence not only is a potential cause of death, but also can be part of a lived experience. When studying violence, archaeology goes beyond identifying it as absent or present, and asks questions about who gets targeted by it, and what this pattern tells us more broadly about the society. How is the violence gendered? How is it related to structures of inequality? Is it linked to conflict between groups? The bioarchaeological approaches to nonlethal violence and how it affects the lived experience of people allow us to ask questions about power and suffering (Martin

et al. 2012). All these questions must be framed within both a broader comparative understanding of violence in human societies and a consideration of the uniqueness of particular cultural contexts. Again, we see how a transdisciplinary archaeology is a case of where the whole understanding is greater than a simple sum of analyses and interpretations. When physical violence or a more silent killer like starvation is the cause of death, the story inscribed on the bones of the dead may be contextualized with all the other information we have about a period in time, allowing us to decipher cases of bodily violence, trauma, suffering, and survival as common or exceptional, ultimately allowing us to get to a better understanding of lives and deaths in this past context.

Death is also a profoundly cultural and social phenomenon, and any study of archaeological mortuary features relies heavily on this understanding. When a person dies, the survivors are left not only with the abstract problem of loss and grief, but also with the concrete biological product of death: a cadaver. The way in which the body is handled after death—which is what we as archaeologists encounter the remains of—is highly variable across cultures and deeply rooted in ontology. To engage with these remains therefore requires a thorough consideration of handling the dead as a social practice that influences but is also influenced by the cadaver. This is the case regardless of specific research question (e.g., about social status, inequality, other aspects of identity, violence). There are fundamental epistemological reasons for this. Without an understanding of the cultural context we are unable to assess the validity of our data, whether it is representative or relevant for the kinds of questions we are asking. But the consideration of dealing with death and the dead also has an ethical dimension that is equally important. As archaeologists, we often work with the remains of people who have not given consent. The least we can do to uphold our professional standards is to explicitly acknowledge that the remains we work with are human remains, often from ritual contexts.

Concluding thoughts

Archaeology is not in crisis. Humanities and social science-driven archaeology is developing

growing practical and intellectual connections with scientific archaeology. This positions our discipline as a dynamic and promising field for robust and thoughtful transdisciplinary collaboration. But as with any academic field, we are facing tensions in moments of growth, and it is imperative that we reduce them before they undermine the dynamic, collaborative work that is being done. To accomplish this, we need to follow a few best practices of transdisciplinary research, including recognizing the dependency we have on one another's insights; becoming literate enough to be able to assess the information provided by other specialized research fields; and explicitly crediting the "other side" for the research they have accomplished, which in turn has stimulated new questions asked.

SEE ALSO: Archaeological Sciences; Archaeology; Biogeography; Burial Excavation; Embodiment; Mortuary Analysis; Osteology

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Humanity and Animality

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Humanity is normally understood as that which is associated with human beings, most notably cognitive faculties and psychological characteristics that are generally attributed to human beings and (sometimes wrongly) perceived as unique to humans. These traits are, beyond pertaining to all things human, cognition in the form of rationality, reason, and intellect. Morality and compassion are other traits associated with humanity. This article is mainly concerned with the above description of the understanding of humanity. However, associated understandings of humanity are also important to bear in mind when considering the implications of this definition to archaeology. Associated understandings include:

1. The academic disciplines thought of as the umbrella term humanities (i.e., archaeology, literary studies, languages, history, arts). Universities and other educational institutions are ordered according to this understanding of academic subjects, with separate humanities faculties.
2. Humanitarian work normally associated with charities and non-governmental organizations (NGOs) that work towards bettering living conditions for others.
3. Human nature—the understanding of what it is to be a human and what sets humans apart from other types of beings, more specifically psychological characteristics that are common to members of the humans species, hereunder virtues such as morality and empathy.

Animality is understood as particular traits that are associated with the animal nature. It describes perceived common traits of nonhuman

animals and is used to describe that which is not mindful, nor virtuous, like base instincts, biological drives, and natural, unrestrained, unreasoned responses to physical drives or stimuli. The animal nature is seen as a direct expression of animal behavior, which is interpreted as being devoid of human cognitive abilities such as rational thought and intellectual reasoning, and psychological characteristics such as empathy and morals. For example, more specifically, lack of capacity for language is associated with lack of cognitive functions such as memory, intention, planning, and ultimately agency. Thus, animality encompasses the “brute beast,” governed by pure instincts.

Therefore, it is to a large extent defined in relationship to, as well as seen in opposition to, humanity and denotes what humanity is not. Traditionally in western science, animals of various species are understood as beings that lack the faculties of humans, such as intentionality, cognition, language, creative art, and the ability to create and sustain complex societies. As will be described below, new and ongoing scientific experiments—particularly in biochemistry and neuroscience—are increasingly challenging this understanding of animal nature and thus the concept of animality.

Archaeology is founded on the basic premise that humanity and humans, are an entity apart from—although not physically separated from—the rest of the natural world. Humanity is understood as expressed and materialized as human cultures. These past cultures make up the main study area of archaeology. From the point of view of archaeology, humanity consists of traces of humans and their activities, hereunder hominids, and the traces of the societies that humans have lived in. A presupposition that humans are a species set apart from all other (animal) species underlies this way of thinking. Inasmuch as natural sciences play a part in archaeological interpretation (e.g., paleobotany and osteology) they are relevant when they can inform on how past human cultures left imprints on the natural world, such as the cultivation of grains and the domestication of animals. A

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human killing a bear is therefore of interest to archaeology, and a bear killing a human—but not a bear killing a bear.

Main strains in western philosophy have solidified this way of thinking, particularly in the Enlightenment movement, which modern academic traditions rest on. Famously, the philosopher René Descartes (1596–1650) with his ideas of humans as beings with minds and souls, as opposed to animals as automata, phrased enlightenment in his cogito sentence: “I think, therefore I am.” His ideas have been very influential regarding how humans in the western world have come to understand themselves as just that (e.g., Brentari 2016).

Descartes and other philosophers have been instrumental in creating an ontological system with a hierarchy of beings with humans on top, and these notions are mostly implicit and unexpressed. Philosopher Carlo Brentari suggests that

The superiority of man ... is seen as depending on the presence of an element, structure, or instance that is ontologically different from all other entities in the world, which grounds and justifies any other form of superiority. (2016: 127)

There is, according to this understanding, a difference of kind between human and nonhuman animals. Archaeology and its place in the humanities is also prejudiced by the tacit assumption of man’s superiority.

Lately, academics have begun to question human superiority. Anthropologist Anna Tsing (2012) describes traditional science as human exceptionalism, and as a “normative fantasy” in our culture. She claims that

Science has inherited stories about human mastery from the great monotheistic religions. These stories fuel assumptions about human autonomy, and they direct questions to the human control of nature, on the one hand, or human impact on nature, on the other, rather than to species interdependence. (2012: 144)

But, she posits, “What if we imagined a human nature that shifted historically together with varied webs of interspecies dependence?”

Sometimes animality has been referred to as traits in humans that are seen as undesirable, like lack of restraint in various ways, hereunder sexual instincts, gluttony, unacceptable violence (Brentari 2016: 128)—the alleged “animal nature” of man. This reveals some of the problems with these terms—humanity is an ideal rather than an actual description of what it is to be human. Humans are also, biologically, animals, and as members of the animal kingdom humans therefore share many traits and characteristics with other animal species, from anatomical traits such as a spinal column and a digestion system, and manner of reproduction, to communication systems by sound and bodily gestures. Lately, research on animal and bird cognition has taken giant steps forwards, as researchers are increasingly improving designs to study animal cognition not as a lesser copy of human cognition but as unique to each species. These studies include parrots that can distinguish colors, shapes, can spell and do maths, corvids that use tools, can evaluate speed limits on roads and whose intelligence seems to be converged with primates, and primates that can do advanced maths and recognize and remember numbers at a speed that no human can hope to achieve. Also, insects such as termites, bees, and ants form complex societies with advanced communication systems, and beavers create built structures. Not just cognitive structures have come under scrutiny, studies also show that animals may feel empathy and act accordingly, as well as having a moral compass (e.g., De Waal 2009). These examples demonstrate that animals share more traits with humans than previously recognized.

What is it, then, that separates humans from the rest of animal kind? Some argue that the separation between humans and animals is of degree rather than kind, i.e., that different animal (hereunder human) species share basic core traits, and they differ in the level of ability and capability, rather than a black and white have or have not. Thus, humanity and animality are, in terms of physicality, not mutually exclusive. In fact, common usage of animality includes humans (although undesirable and so-called base human instincts, actions, thoughts). Rather, according to the common usage of the terms, humanity and animality are sliding scales.

Humanity is, according to this definition, the gold standard of rationality, however, archaeology (and anthropology) teaches us that each culture has their separate understandings of the world and “how it works,” in other words, different ontological rationales. When considering past societies it is therefore important to bear in mind that ideas of what is rational is not a cross-cultural given, rather, understandings of the ontological ordering of the world will normally differ between societies. Likewise, ideas of what constitute the natures of different beings are subject to different understandings. The definitions that archaeology, as well as normative sciences, operates with, regarding humanity and animality are, thus, a historically specific product of the way western science understands the ontological nature of being. This is important to bear in mind when studying past societies, in which radically different understandings of the nature of being would have been formative for every aspect of life, such as the social, economic, and religious parts of existence.

Further, the lives of humans and animals should be studied in particular historical settings so as to allow for an investigation into the unfolding of culturally and historically situated ontological status of beings. This entails that just as different categories of humans are studied—based on gender, age, social status, and so on—rather than regarding humans as one undifferentiated category, animals should also be considered according to species, age, and gender.

The archaeological discourse on animals has traditionally been devoid of the potential agency of animals, but rather focused on animals as either container for human symbolism, as economic strategies, or as conglomerations of passive materials for humans to shape (Armstrong Oma and Birke 2013). As in the humanities at large, human agency has been granted supremacy. This attitude has seeped into archaeology by way of the Enlightenment roots of the humanities. In a philosophical sense this entails that ontologically the nature of being is the nature of human being; the nature of action is of human action (Johannsen 2012: 305). But animals are more than cultural abstractions: what is lacking is considerations of the animals *as themselves*. However, currently there is a growing recognition that many animals possess characteristics

such as intelligence, emotion, and awareness that vary from humans by degree rather than kind (Shapiro and DeMello 2010). Animals are alive, active participants in their worlds, and the spaces where those worlds intersect and enmesh with humans are often messy and difficult to divide into clean compartments. In addition to how humans “use” them, animals often take part in subjectified relationships with humans that impact both species at various levels of scale. For example, Birke, Bryld and Lykke (2004: 172–3) describe how rats in labs defy their definition as “data” for animal experiments by requiring that humans facilitate their biological and social needs and perform accordingly.

The debate as to which factors should be present to qualify as agency ranges from intentionality, free will, and morality. New research in biology and ethology is constantly challenging the common perception of such qualities as human-only and bridges the gap between humans and animals. McFarland and Hediger (2009: 8) puts it thus: “no matter how we consider agency, the result is that either humans are more like the other animals or the other animals are more like humans than we have comfortably thought in the past.”

Bearing this in mind, it may in a number of ways be relevant to archaeology to also include animals as social agents in research on past societies. One poignant example is domestication, which led not just to domesticated animals becoming a “walking larder” but also led to new ways of living together with different species. Domestication led to changes beyond the genetic engineering of the domestic animals that came to depend upon humans. For example, a specific material culture, architectural structures, and interactions with the landscape that led to environmental changes. A useful approach in understanding how animals played a part in such processes is found in the growing interdisciplinary field human–animal studies.

Human–animal studies (HAS) is a newly established interdisciplinary research field that has seen an immense growth in the last few years (Shapiro and DeMello 2010). Several journals are devoted to the field, such as *Society and Animals*, *Anthrozoos* and *Humanimalia*, and Brill publishes a series called HAS (short for

human–animal studies). Large international conferences are held, for example under the umbrella of the loosely knitted organization Minding Animals.

The objective of HAS is to examine the complex and multidimensional relationships between humans and other animals, and it “embodies a sustained interest in understanding and analysing how we humans relate to and make sense of other species” (Birke and Hockenhull 2012: 3). HAS comprises work in areas of study such as psychology, sociology, anthropology, political science, history, literary criticism, and other disciplines in the humanities (see <http://www.animalsandsociety.org/pages/human-animal-studies>). A plethora of research questions emerge from this platform, examples range from animal-assisted therapy, wildlife conservation, to questions of animal advocacy, and rights. An outspoken position of animal advocacy is frequently found. Shapiro and DeMello (2010) point out that the combination of advocacy with scholarship is currently perceived as less threatening, as the thrust of contemporary philosophy of science challenges the traditional view that it is possible for a scholar not to have a position on the material under investigation. The thing is, as Birke and Hockenhull (2012: 4) point out, understanding multiple forms of human–animal relationships “requires thinking laterally, to interrogate widely diverse ways of observing and theorizing, and to be able to draw on diverse disciplinary approaches.” This broad platform includes, for many, a personal investment with the issue at stake.

For a large part, the archaeological literature on animals is, as previously stated, within the bounds of animal studies, and perceives animals as human constructs. However, there are exceptions, namely archaeologists that work within HAS (see for example *Society and Animals* 21 (2) from 2013, which is a special issue on archaeology). HAS allows the animals to be objects of study, but they are also sanctioned as subjects. Academic works within this field own up to the fact that for animals to be studied as social constructions—and to understand the meanings of those constructions—the question of who and what the animal in itself is must be addressed first, such as their social and cognitive abilities and behavior (Shapiro and DeMello

2010). Meaning emerges through experience, for human and nonhuman animals both; also in the way humans understand and interpret the inner world of animals.

Recent research on biochemistry has demonstrated that it is indeed possible for humans to grasp the emotions and feelings of other species, by way of the biochemical phenomena of the hormone oxytocin (Olmert 2009) and brain cells termed mirror neurons (Iacoboni 2008).

Archaeology holds the potential to be a very important discipline for the development of HAS since archaeology can add a unique diachronic perspective, exploring the coevolution of species, and adding time depth to issues that concern human–animal studies (Armstrong Oma and Birke 2013). In the deepest sense, archaeology can, by way of studying human origins, ask fundamental questions about what it is to be a human animal, and thus decenter the human species, pushing us off our self-appointed throne of species supremacy (see Gittins 2013).

SEE ALSO: Birds; Bodies and Embodiment; Bones and Ivory; Cattle; Companion Animals; Conservation of Bone, Horn, and Ivory; Coprolites; Critical Theory; Dairying; Domestication; Domestication of Equids; Environmental Management with Livestock; Ethnoarchaeology; Fish; Interpretation; Knowledge and Inference; Material Agency; Mind and Cognition; Osteology; Personhood and Objecthood; Pigs; Realist Philosophies of Science; Science and Politics; Sheep and Goats; Taphonomy; Time and Temporality; Zooarchaeology

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Inhabited Landscapes

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One of the many delights of undertaking indigenous archaeology and working closely and collaboratively with indigenous communities is that you often hear statements that jolt you out of the complacency and normativeness of western thinking. In early 2016, during the course of a conversation with a senior elder of central Torres Strait over why government authorities need to engage Torres Strait Islanders more meaningfully in local environmental management, I was told simply that “We are the environment.” I knew immediately that this statement was not a reference to a western romanticized notion of Torres Strait Islanders being a part of nature or living in harmony with nature. This statement had a more profound ontological message that sidestepped western dualist thinking about a division between culture and nature, and between people and the environment. It signaled that the environment does not sit outside of humanity awaiting engagement (and management) but exists only in its relationship *with* people. This human-centered view of the environment goes to the heart of conceptualizing and understanding inhabited landscapes.

The theoretical work of the anthropologist Tim Ingold heavily informs archaeological conceptualizations of inhabited landscapes. Critical is Ingold’s (1993) phenomenological dwelling perspective which draws on notions of dwelling and being-in-the-world, expounded by the philosopher Martin Heidegger. In this conception, landscapes are an enduring record of human dwelling and the lives and associated labors of past generations. As dwelling by definition is an ongoing process, human–environment interactions are similarly ongoing. Thus, inhabited landscapes are always under construction and works-in-progress, with intrinsic and inherent temporality.

A dwelling approach to inhabited landscapes challenges the culture/nature duality of western thought. Externalization and objectification of the environment are expressions of a Cartesian dualist ontology developed as part of European Enlightenment thinking in the eighteenth and nineteenth centuries. In this connection, anthropologist Philippe Descola (2013) explores the development and expression of the nature/culture dualism in western thinking and how this contrasts to the animistic and totemic ontologies of other societies, especially indigenous peoples of the New Worlds of the Americas and Australia. Descola points out that in a western dualist (naturalistic) ontology, nature (and by extension the environment) is positioned as an external and autonomous entity to humanity such that it becomes available for objective study. As such, archaeologists come to rely on scientific and universalistic characterizations of an external nature (environment) to which diverse peoples and cultures adapt.

Although archaeologists have worked closely with paleoenvironmentalists over many decades to develop robust scientific techniques to characterize the environments of peoples of the past, such characterizations are only one dimension of landscape archaeology. Researchers need to be aware that an approach that ontologically, epistemologically, and analytically separates environment as an externalized and objective entity to culture produces information that is relevant to a culture/nature dichotomy. In this conception, the environment has an objective reality beyond people who subjectively perceive and engage with only a subset of the environment as they enculturate spaces as places. In contrast, an archaeology of premodern-inhabited landscapes sees nature (and the environment) as an internalized and subjective entity that is understood through bodily immersion and experience. Environmental perception and engagement are not part of the language of inhabited landscapes (Thomas 2012).

Each generation inherits not only cultural sites and places of meaning, memory, and history,

but also environments and ecological processes which have been molded, manipulated, and transformed by their ancestors. This dynamic relationship has parallels with what the evolutionary ecologist John Odling-Smee (1994) refers to as niche construction, whereby the cultural inheritance of societies also includes ecological inheritance and the continuity, either intentionally or unintentionally, of humanly modified ecological processes. The result is that the relationship between people and their environment is not only dynamic but also mutually constitutive. Thus, inhabited landscapes take shape as the cumulative product of the mutually constitutive and mutually transformative interplay of people–environment relationships and interactions. Ingold (1986, 2) reminds us that “an environment can only be defined relative to a being or beings whose environment it is.”

No landscape or environment comes ready-made for human habitation. Something has to change: either cultural behavior and/or the environment itself. Because such changes are invariably cumulative, the process of change is never a one-off event because the desired state of inhabitation is always unfolding and always a work-in-progress. Thus, the quest for archaeologists is to characterize past environments not as external backdrops to cultural practices but as internal expressions of the rhythms of life and the cumulative products of cultural practices and long-term human interactions. To assume that particular peoples of the past had no impact on their environment not only implies that their environment was presuited for inhabitation, but also posits a passive ecological state virtually unknown for higher-order organisms. This process is analogous to the process of owning shoes. We purchase shoes with an understanding that it is only through the process of wearing the shoes that they become worn-in as they accumulate subtle morphological modifications to increasingly mold to the unique form of our feet and our lifestyle. As such, our shoes are always a work-in-progress, accumulating historical and symbolic dimensions through the historical process of wearing. Inhabited landscapes are worn-in landscapes.

A critical point to remember with inhabited landscapes and a dwelling perspective is that

new environments are not engaged in externally and perceived through the subjective lens of culture. Even if people enter places never visited or seen before, they have an immediate prediscursive preunderstanding that makes interaction possible. The plants, animals, topography, and even weather may be unfamiliar but never so unfamiliar that it is impossible to traverse through that landscape. Indeed, new environments neither exist outside of our own embodied interactions with such places nor have an objective reality beyond that interaction. It is for this reason that no environment is truly alien, even in situations of colonization where people enter new worlds. Colonizers do not enter new worlds and begin to modify such places such that dwelling can take place. Places are modified because the decision to stay has already been made. In an analogous sense, every archaeological site survey is a form of embodied dwelling such that it is possible to identify new artifacts such as flaked stone tools of which no two are identical.

A key environmental approach to operationalizing inhabited landscapes is engineered or constructed landscapes and the three processes of inclusions, exclusions, and transitions. Inclusions involve the deliberate movement of selected plant and animal species by people from one environment to another. While the best documented and understood archaeological example of this process is the movement of domesticated plants and animals, Pleistocene hunter-gatherers also employed this process. Exclusions are the deliberate quarantining of areas from the introduction of certain plant and animal species usually to avoid negative environmental impacts. For example, the spotty distribution of domesticated pigs across the Pacific may relate to different island communities responding to the known capacity of pigs to destroy horticultural gardens. Introduction of pigs comes with a requirement to build fences around gardens, whereas exclusion of pigs avoids the need to build garden fences. Transitions are the most common form of environmental engineering documented by paleoenvironmentalists. This process involves in-situ manipulation of endemic ecological processes to bring about some form of desired environmental change, usually enhancement of particular resources. Perhaps the best documented example of this process is landscape burning to increase the availability of

selected plant and animal species. With all three processes, intended changes may also have short- or long-term unintended consequences. In some cases, the long-term cumulative impact of unintended consequences may present new resource opportunities. For example, slope erosion through landscape burning may lead to coastal progradation and new opportunities for habitation and cultivation of crops. Similarly, long-term occupation of campsites by hunter-gatherers can result in unintentional establishment of garden groves through cumulative germination of discarded plant foods and cumulative soil fertility from organically rich occupation deposits. In this sense, inhabited landscapes are worn-in landscapes and worn-in environments.

Environmental change linked to long-term dwelling creates a situation where all inhabited and constructed landscapes are to varying degrees also domesticated landscapes (Terrell and Hart 2008). In this formulation, the concept of domesticated landscapes has particular analytical potency for hunter-gatherers where long-term use of particular plant and animal species alters local ecologies. That is, these ecologies only maintain their altered state as a result of constant human use and intervention. As such, and in keeping with the concept of inhabited landscapes, all domesticated landscapes are constantly under construction and always unfolding as works-in-progress. While, in some circumstances, intensive intervention in local ecologies may result in formal domestication of plants and animals (e.g., morphological and genetic changes), such formal change is not a necessary condition of domesticated landscapes. In other circumstances, alteration of local plant and animal ecologies may be indirect through alteration of related environmental features. A good example of this indirect alteration is manipulation of local hydrologies through modification (e.g., damming) of local waterways to enhance the habitat, availability, reliability, and capture of key aquatic resources (e.g., birds and fish). Clam gardens on the Northwest Coast of North America indicate that such manipulations also extend to marine environments and seascapes.

Intended and unintended consequences reinforce the view that constructed landscapes are

always in a state of emergence and are never finished. Furthermore, constructed landscapes are recursive such that people shape environments but environments also shape people. From a dwelling and mutually constitutive perspective, people can be seen as orchestrating the deterministic qualities of environments of their own construction. In this connection, the anthropologist Roy Ellen (1982) makes the important point that many correlations between culture and environment are in fact correlations between human behavior and the ecological products of that behavior in the form of a modified environment.

The notion of constructed landscapes as the temporalized cumulative product of past human actions and ongoing human interactions reveals that inhabited landscapes are also inherited landscapes. That is, each generation inherits not only the products of their ancestors' labors but also the practices to allow potential continuity of processes of environmental interaction and manipulation. While each generation exercises agency and can choose whether or not they wish to continue such processes into the future, they have no choice in the inherence of the products of the past application of such processes. It is in this context that all inhabited landscapes are also historically contingent landscapes (Barton et al. 2004). Yet such landscape inheritance is rarely complete beyond the products of the past labors of the previous generation in terms of modified environments and material objects. As the generations pass, the potential for past landscapes to endure decreases as generations decide to invest less and less in the maintenance of processes that ensure continuity of the form and knowledge of the fruits of past labors. In extreme cases, the fruits of past labors become pruned and transformed beyond recognition and even forgotten about and lost. Archaeological research is founded upon a desire to selectively rediscover and reimagine the material expressions of these forgotten and lost labors.

Perhaps the most challenging aspect of a dwelling perspective to inhabited landscapes is the place of nonhuman persons and spiritual entities. Anthropological research reveals that indigenous people inhabit animate, sentient, and intentionalized land- and seascapes where the social and agentive domain of humanity is not limited to human beings but also

includes many plants, animals, objects, and spirits (Descola 2013). As such, humans interact with this broader humanity not through ecological relationships and the objective currencies of resource maximization and calories but through social relationships and the subjective currencies of reciprocity and morality. As such, an important dimension of the inhabited land- and seascapes of peoples of the ancient past is spiritscapes and spiritual forces that were engaged ritually, often at formally constructed sites (e.g., shrines), as a normal part of dwelling.

Of immediate concern is the role of spiritual forces in human–environment interactions and the extent to which spiritual forces could be manipulated by people to alter the nature of such interactions. For the most part, people engaged spiritual entities and associated forces through specialized ritual performances. These interactions usually were associated with increasing the ability of hunters to obtain prey (both terrestrial and marine) through what are often referred to as hunting magic rituals, and with increasing the availability and fertility of selected plant and animal resources or altering key elements such as wind and rain through what are often referred to as increase rituals. In some respects, hunting magic and increase rituals can be seen as a dimension of engineered or constructed landscapes. However, a dwelling perspective redirects attention away from such a utilitarian perspective to one where such rituals form part of the ongoing lived expression and experience of the ontological status and relationality of humans and nonhuman persons.

The spiritual dimensions of dwelling and inhabited landscapes also involve the agency of ancestral beings, including the ancestral dead. Often this ancestral agency, power, and potency is strategically engaged, released, and expressed through hunting and increase rituals. While such interactions have an immediate impact on people, they also can have more profound implications in terms of ensuring continuity of the world. This process is illustrated well by the Dreaming ontology of Aboriginal Australians and their associated landscape concept of country. For Aboriginal Australians, ancestral Dreaming beings created not only the world but also humanity. Dreaming beings invariably are linked to, and often embodied as, different

features in the landscape of their creation and transformation. Land ownership among Aboriginal groups is usually linked to these Dreaming beings and emplaced features. With the rights to land ownership and associated resource use come ritual responsibilities to ensure continuity of Dreaming being forces and associated resources. Although ancestral creator beings existed before people, it is only through human dwelling in the totemic landscape that these ancestral beings and forces are renewed and become efficacious and generative in the present. Indeed, it is only through the temporal process of dwelling that Aboriginal people increase in age and seniority to take on the corresponding increasing complexities of Dreaming knowledge and law that are expressed through rights, rituals, and responsibilities. Critically, Aboriginal people learn about their ancestral past by moving through the landscape in the company of elders (Morphy 1995). The ancestral past (as the basis for Aboriginal sociality, identity, and belonging in the present) is revealed as a dimension of place not time. In this conception, the inhabited landscape as an ancestral landscape is expressed and given form through human experience.

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Interpretation

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An interpretation is a theoretical or narrative account of “something,” whether it be facts, events, persons, or texts, that makes that “something” comprehensible. In archaeology, the “something” in question is the archaeological record: archaeology, being the discipline that studies the human past through its material remains, offers interpretations of that past. Interpretation makes sense of archaeological evidence (Tilley 1993). Archaeologists must engage in an “interpretive leap” when moving from excavated data to final report (Trigger 1996). They do this by way of what Gamble (2008) has called the “archaeological imagination.”

In the human sciences, more generally, it is possible to distinguish “historical interpretations” from “scientific explanations.” Historical interpretations are based on human experience, understanding, and language, whereas scientific explanations are based on observations that are abstract, constructed, and theoretical. In archaeology the concept of interpretation has gone through a number of different theoretical phases. Each phase has bordered on historical interpretation or scientific explanation to varying degrees. A broadly culture history approach remains a mainstay of archaeological interpretation. Thomas (1995) argued that much of the work produced by academic archaeologists in the United Kingdom, for example, still broadly conforms to this approach. Culture history approaches in archaeology prioritize the gathering of data, the establishment of facts, and the creation of appropriate classifications of that data. An emphasis on inductive reasoning, bringing this approach into the borderlands of scientific explanation, where the interpreter moves from their specific observations to making more general claims that are supported by their observations is a central plank of culture history

approaches. It is chronological and geographical ordering of data that is paramount for culture history approaches and it is new data, rather than new interpretive frameworks for that data, that is believed to drive the development of archaeological understanding. As witness to this, Gamble (2008) notes that Gordon Childe’s *The Dawn of European Civilisation* went through six editions between 1925 and 1957. Interpretation, historical or otherwise, beyond what can be discerned by the attentive archaeologist looking out for indications of change (in both chronological and geographical directions) in the data of the archaeological record, is typically regarded as speculation (Gamble 2008, 23).

In the 1940s and 1950s, owing to a generalized cultural positivism (see POSITIVISM) and/or empiricism (see EMPIRICISM), interpretations of the archaeological record were taken to be subjective—matters of opinion without lasting importance (Trigger 1996). For archaeologists such as Glyn Daniel, Stuart Piggott, and Christopher Hawkes it was archaeological data that was taken to be central to the discipline. Whereas data are objective, interpretations, by contrast, are shaped by intellectual fads and can be undermined by new and improved understanding of data. Figures like Daniel, Piggott, and Hawkes were, in part, reacting to the influential work of idealist philosopher and archaeologist Robin George Collingwood (1889–1943) who had denied that facts and theories were distinct from one another. Collingwood argued that archaeological interpretation is an activity whereby a modern archaeologist attempts to relive the past in their own mind by way of their ideas: these ideas are about the ideas that past peoples had in their minds. It is these past ideas that shaped the archaeological record. By reconstructing these past mental activities that shaped events, modern archaeologists could hope to articulate the archaeologically visible dynamics of ancient cultures (Trigger 1996, 303–305).

Writing in the 1970s during the heyday of “new” or “processual archaeology,” David Clarke argued that archaeologists utilize five bodies of

theory in their intellectual leaps from data to final report, the final body of which he termed “interpretive theory.” Clarke was skeptical of the broadly intuitive approach used by culture historians in the construction of their historical narratives. He believed that these narratives proceeded without a duly rigorous analysis of the archaeological data which would extract as much information on past behavior as possible. Clarke went so far as to suggest that such narratives represented an “irresponsible art form” (Trigger 1996, 430).

The first body of theory noted by Clarke is “predepositional and depositional theory.” This covers relations between human activity, social patterns, and environmental factors, and with the samples and traces found in the archaeological record. The second body of theory, dubbed “postdepositional,” examines natural and human processes affecting the archaeological record. This includes factors from natural erosion to traces of plowing. Third, “retrieval theory” deals with relations between what survives in the archaeological record and what is recovered in research. Fourth, “analytical theory” deals with how the data recovered from the archaeological record are treated. As such, analytical theory includes varieties of classification and modeling, testing, and experimental studies. Finally, the fifth body of “interpretive theory” concerns the relations between the archaeological patterns discerned at level four (analytical theory) and the unobservable ancient environmental and behavioral patterns that they express. As Trigger put it, Clarke’s interpretive theory “infers the processes that predepositional theory explains” (Trigger 1996, 432). In Clarke’s view, the challenge facing archaeologists is to establish appropriate bodies of theory for each level of analysis. This will involve incorporating analyses from the biological and physical sciences as well as from archaeology, since the human sciences are taken to be restricted to the predepositional and interpretive levels of analysis. Clarke believed that taken together in its entirety, this “theory,” in combination with more broadly philosophical issues relating to logic, metaphysics, and epistemology, would combine to create a truly scientific archaeological discipline (see SCIENTIFIC PRACTICE).

Processual archaeology conceived of archaeology as anthropological science. It is not

specifically allied with humanistic disciplines, such as history. Processual archaeologists value explanation, via methodologies modeled on the hard sciences, over description and/or historical interpretation. Archaeological explanations will incorporate particular observations of the material past drawn from the archaeological record and will incorporate these into cross-cultural generalizations that relate to both natural and social processes. This emphasis on processes is where the designation “processual archaeology” originates. Earlier emphasis on “laws of human behavior” in archaeology is replaced by a concern with the formative processes of the archaeological record itself. Identification of regularities in the record will allow for inferences about processes “to be made from material remains” (Shanks and Hodder 1995, 3). Processual archaeology, which took for itself the title of “new archaeology,” aimed to discover knowledge of the past that, in aspiration, was objective, neutral, timeless, and singular. Despite these aspirations, the fate of interpretation in archaeology did not stop there. Starting in the 1970s, an alternative to this approach began to develop. This alternative tendency was named “post-processual archaeology” by Ian Hodder in 1985. In 1991 it was dubbed “interpretive archaeology,” again by Hodder (Hodder 1991; Trigger 1996). The epithet “interpretive archaeology” is intended to be a positive label for a number of diverse approaches grouped under this banner, in place of the lesser relational title “post-processual” (Shanks and Hodder 1995). Hodder described interpretive archaeology as being characterized by a “hermeneutic method,” and by 1995 he and Michael Shanks suggested that the term “interpretation” itself is the term that will help to clarify current debates in archaeological theory between processual and post-processual archaeology in the English language.

Shanks and Hodder describe interpretive archaeologies as follows: archaeology is a material practice in the present that makes “things,” interpretations, narratives, reports, and so on out of the archaeological record. These “artifacts” are no less truthful for being produced by researchers. In the foreground of the archaeological enterprise is the interpreter, the archaeologist. Interpretation is a form of practice that requires the interpreter to take responsibility for their interpretations. Like other social practices, archaeology is concerned

with “meanings.” That is, the job of archaeology is to make sense of things and, because of this, archaeology will be inherently interpretive. Importantly, because it is an interpretive practice, the project of archaeology will be ongoing: no final authoritative or definitive account of the past is possible. As a process concerned with meaning or understanding, the concern with causal explanation is diminished in interpretive approaches. Different interpretations of the same subject matter are possible: multivocality (see *PLURALITY AND MULTIVOCALITY*) is embraced and so a plurality of different archaeological interpretations can be produced. These interpretations will reflect different needs and desires. Interpretation is creative (see *CREATIVITY*), but it is not uncritical. The needs and desires of interpreters and of groups and communities who have an interest in the material past must be recognized (Shanks and Hodder 1995, 5; Jones and Alberti 2013).

The question “What is interpretation?” is still an open one in archaeology (Jones and Alberti 2013). Over the last decade or so, theoretically oriented archaeologists have moved away from asking broadly epistemological questions, such as “What constitutes archaeological knowledge?” and toward asking ontological ones, such as “What is the nature of archaeological thought?” What Lucas (2012) has called the “current interpretive dilemma” is bound up with questioning the underlying ontological commitments and metaphysical assumptions of archaeological discourse. Rather than seeking to remove interpretation as the primary goal of archaeology, contemporary theoretical archaeologists seek to question the nature of the interpretive process and of the archaeologist’s role in it. This emphasis on questioning follows the identification of a worry that one of the consequences of the emergence of interpretive archaeology, which foregrounded the role of the interpreting archaeologist in the present, was to construct a vision of past human agents as essentially “interpreting subjects.” While archaeologists might always aim at providing an interpretation of the archaeological record, archaeological questioning has now recognized that interpretation and reality are coemergent. That is, all practices, including archaeology, are taken to be “fully relational and constitutive” (Jones and Alberti 2013, 15). This

change in perspective in contemporary theory moves away from placing the interpreting subject, as an individual identity, at the center of things. This move is also skeptical of the view that the human subject is the only being capable of action and interpretation. Human subjects too are taken to be fully relational and performative constructions. The interpreting subject is rethought as relational and as something that emerges within a set of unfolding relationships. The shift from epistemology to ontology in archaeology does not herald the “death of interpretation” or the “death of the interpreting subject,” but it does place emphasis on the very constitution of “humanity,” taken as a specific subjectivity, in both the past and the present, as well as questioning the constitution of archaeological interpretation. Rather than representing a radical break with earlier interpretive archaeologies, recent theorists have instead revisited a shared group of influences, such as Martin Heidegger, Michel Foucault, Gilles Deleuze, and Felix Guattari, with fresh eyes and questions, and so possibilities for interpretation.

SEE ALSO: Archaeological Classification; Archaeological Record; Archaeology; Heritage Interpretation; Material Agency; Material Culture; Mind and Cognition; New Materialisms; Symmetrical Archaeology

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Knowledge and Inference

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Archaeological knowledge consists of descriptive statements and explanatory hypotheses, and both of these are intertwined with images. Descriptions pertain to observations made during field and laboratory research. Explanatory hypotheses, on the other hand, are solely the product of inferences. The latter play a most fundamental role in the formation of archaeological knowledge. The everyday work of archaeologists entails that they infer from the residues of past actions the nature of those actions. Observing what is at hand in the present, they work back to the unobservable circumstances that could have brought it about. This process has repeatedly been considered to be analogous to the “method of Zadig” (briefly, the identification of an animal’s species and condition from the tracks it leaves on the ground). In fact, it is considerably more complex. That complexity is due to the palimpsest-like nature of the archaeological record (see *ARCHAEOLOGICAL RECORD*).

Not all of the archaeologist’s knowledge consists of inferences concerning past actions, however. A substantial portion of it consists of descriptions, in technical language, of observations made in the course of field and laboratory research. Such descriptions may at a later stage of the research be used in inferences about past actions. Even when they are not, however, they are still important in knowledge formation: They force the archaeologist to pay attention to details without judging in advance their significance. For that reason, the requirement for adequate descriptions is a standard part of the protocols to be followed in field and laboratory research. When researchers do not adhere to it, their conclusions are likely to be regarded with skepticism, and even ignored by the scholarly community. Because of the importance accorded to descriptions, learning to describe the observable in

appropriate technical terms is an essential part of a novice’s training.

As a rule, descriptions (to a lesser extent, explanatory hypotheses too) are accompanied by images: photographs in various scales, from microphotographs to satellite imagery, drawings, and graphs. Such images carry considerable cognitive weight. They are of equal value to the descriptions and are to be consulted along with them. Their great virtue is that they contain knowledge that cannot be effectively rendered in propositional language, for example, textures, spatial relationships, and synopses of quantifiable data. Archaeology’s knowledge claims have long been substantiated by reference to such imagery. Beside their documentary role in the archaeologist’s research report, images have many other uses. They also serve, for instance, as aides-memoires for the professional and as working objects (*Arbeitsobjekte*) in modeling alternative explanatory hypotheses. They serve as devices for training the novice’s eye. Placed side by side on the printed page, they enable comparisons among artifacts from different geographical locations and periods, and they make possible the communication of one’s discoveries to the world at large. In short, imagery is present in every stage of the archaeologist’s formation and professional life. It is essential for his/her training, in field-work, in the documentation of research results, and in their transmission to professionals and the lay public. Archaeological knowledge turns out to be to a most substantial degree visual.

Naturalistic, highly accurate images of archaeology’s artifacts, the work of professional illustrators working together with archaeologists, were already in circulation in the eighteenth century. The crucial role of visual knowledge in archaeology was not, however, explicitly acknowledged until the turn of the twentieth century (Petrie 1904). Discussions at that time concentrated on the merits of photographs (reproduced in archaeological journals by half-tone technology since ca. 1900) in comparison with the virtues and limitations of drawings. Still, published illustrations of archaeological objects in the

first half of the twentieth century were as a rule of a diminutive scale and too sketchy to afford sharp views of the objects depicted. Visual knowledge at the time was transmitted less through published articles than by means of private communication: Archaeologists exchanged quality photographs with one another and also visited one another's excavations and inspected the finds. Their published knowledge claims were based on such first-hand experiences. This began to change in the 1960s, following, on the one hand, the institutional growth of archaeology worldwide and the ensuing rise in numbers of archaeologists and field projects and, on the other hand, the progress of the information age. Theoretical treatises in the 1960s insisted, for example, that ancient artifacts are "congealed information" of a great variety (Clarke 1968, 120) and that archaeological illustrations ought to be "selective"—that is, present the viewer with useful information free of irrelevant detail. Visual knowledge came of age in the course of the next 50 years. The process culminated in the first decade of the twenty-first century, as journals of international circulation began publishing their full content in electronic form. This allowed for the publication of color images of all kinds, including complex, multilayered graphs. Today, high-resolution color illustrations have in large part replaced black-and-white ones, and the trend will, no doubt, be carried further. The advent of color may have had little direct effect on the epistemic substance of archaeology's knowledge claims. It does, however, facilitate perception and, hence, the transmission of knowledge to colleagues, students, and the public. High-resolution color illustrations are, therefore, justifiably regarded today as an improvement over earlier modes of archaeological illustration.

Archaeological knowledge is multifarious par excellence. In the nineteenth century, even before the great antiquity of the human presence on our planet was confirmed by expert observations (in 1859), geology and paleontology were drawn upon in arguments favoring one or another view regarding that issue. Boucher de Perthes in the 1840s, for example, advocated the view of a deep human past on grounds that he had found primitive stone tools in geological strata that also contained fossil bones of extinct mammals. Provenience studies of prehistoric pots, based

on petrographic examination of clay composition, were attempted by the 1860s. Geology, paleontology, and petrography continue to be important sources of archaeological knowledge in the present, but the spectrum of such sources has in the meantime, especially since the 1950s, greatly expanded. Research reports today are routinely coauthored by scores of experts, the majority of whom are devoted to fields only indirectly related to archaeology. Such fields range from palynology to paleogenomics and from the study of sediment micromorphology to stable isotope analysis of marine shell and human skeletal remains, not to mention studies of diet, based on the examination of food residues on ceramic cooking vessels or in Neanderthal dental calculus. In brief, archaeological knowledge in the present is the product of a synergy of agencies, associations that include experts in a variety of specialized fields, laboratories, and their equipment and institutional support, as well as the material agencies of the objects under study (see MATERIAL AGENCY).

While protocols specify procedures in the field and the laboratory, the development of explanatory hypotheses, relating the observable residues to unobservable sequences of past actions, is a creative process constrained by few rules. Furthermore, no enduring "gold standard" exists with regard to what constitutes an adequate explanatory hypothesis. In the heyday of processual archaeology (the 1960s and 1970s) it was first thought that explanations ought to appeal to general "covering laws" (e.g., laws of culture change), just as the natural sciences appealed to laws of nature. A subsequent, more pragmatic version of this stated that the plausibility of a hypothesis depended on its explanatory efficacy for cases beyond the one for which the hypothesis was originally developed (Renfrew 1982). With the turn to post-processual archaeology in the 1980s and 1990s, concerns with the generality of hypotheses receded to the background. Adequate explanations, it was now theorized, had to attend to the uniqueness of each cultural context and to take account of the power and authority embodied in material culture and in the features of the landscape. They also had to pay attention to the human subject, now thought to be historically and socially situated, and, more crucially, to be capable of negotiating

the meaning of material culture and, at once, people's place in the social world (Thomas 1996; Hodder 1992). In discussing his "contextual approach," Hodder (1992, 14) also made it clear that the context of an archaeological object is "all those associations which are relevant to its meaning." Hence, the task of the archaeologist was to identify as many as possible of those associations, whether they could be traced in a single excavation trench or they had to be sought across a continent. Crucial aspects of the object's meaning might thus emerge and important features of the context's configuration might at last be explained.

In its insistence that explanations ought to explain the configuration of individual contexts (though not in its emphasis on the importance of meaning), post-processual archaeology reaffirmed the value of what archaeologists had already been doing and would continue doing in the new millennium. Today's scene is, however, very different from that of the late twentieth century. Researchers now adopt a more pragmatic attitude toward the objects of their research and are more concerned with obtaining sound results from their projects than with applying complex theoretical paradigms. They often revisit, for instance, old problems and enlist newly developed scientific techniques in exploring them. The reexamination and redating of the stratigraphic sequence at Arcy-sur-Cure, Burgundy, France, is a good example, especially since that sequence has long been considered crucial for appreciating the interactions of Neanderthals with Modern humans in Europe and, even, the symbolic capacities of Neanderthals (Hublin et al. 2012). The recently published research on ancient DNA extracted from the skeletal remains of Aegean and European Neolithic farmers also sheds light on a long-standing problem, the process of Neolithization of Europe. These and countless other recent studies are empirical throughout; they have clearly broken away from the theoretical quests of the previous century. Explanatory inferences now are increasingly based on the findings of the natural sciences.

It has long been recognized in the philosophy and praxis of science that theory is underdetermined by observation and, similarly, that observation is theory laden (see PHILOSOPHY OF SCIENCE; Wylie 2002). The underdetermination

thesis holds equally for explanatory inferences in archaeology, no matter how extensively they may draw on the findings of the natural sciences. Simply put, this means that more than one explanatory hypothesis may account for the same set of observations, though perhaps not all equally well. In theory, one decides among rival hypotheses by resorting to *abduction*, that is, inference to the best, or most plausible, explanation. Abduction is by no means a peculiarly archaeological form of reasoning. It is omnipresent in everyday thought and is also regarded by philosophers as a cornerstone of scientific methodology (Douven 2011). Like induction, abduction is ampliative: Its conclusions claim more than is logically guaranteed by its premises. Leaving aside the philosophers' conundrums concerning abduction, the practical question still arises, what makes some explanatory hypotheses better (more plausible) than rival hypotheses? Criteria for this are not altogether absent, but they are too abstract to serve as guides. For instance, a hypothesis that explains more observations is preferable to others that leave crucial observations out of account. But such a hypothesis may also be too general (it may explain too much) to be scientifically interesting. The inexact nature of criteria here may puzzle and dishearten the novice, but not the professional. For the latter, not impressed by the absence of sharply rational criteria, the process by which plausible explanations emerge is still a delicate, one but it has none of the mystique it entails for neophytes.

The expert indeed draws on a large stock of background knowledge relevant to the observables at hand, and his/her expertise consists in part of the ability to rapidly and more or less intuitively dismiss unpromising hypotheses and concentrate on others that deserve serious consideration. Some of the latter may be further corroborated, or weakened, by thought experiments and, further yet, by new empirical evidence. Thought experiments are ubiquitous in archaeological reasoning, but they normally reach the published page in an abridged form that does not readily reveal their hypothetico-deductive structure. An illustration of this practice is found in Arsuaga et al. (1997, 125) which pertains to the processes of accumulation of human and other mammal bones in Sima de los Huesos, Atapuerca, Spain, ca. 430,000 years ago. Were thought experiments of the kind to be analytically described,

it would become clear that they take the form of models from which expectations (E) are deduced, such that “if a hypothesis H is valid, then $E_1, \dots E_n$ should be archaeologically observable,” where $E_1, \dots E_n$ are likely material outcomes of the conditions specified in H . If those outcomes are disconfirmed by observations, the hypothesis is weakened; else, it gains in plausibility, even though, according to the underdetermination thesis outlined above, its truth will remain provisional and negotiable, subject to reappraisal upon further empirical research.

Reasoning through thought experiments is a typically rational way for reaching a plausible explanatory hypothesis. Its hypothetico-deductive structure brings to mind the “deductive-nomological” model of scientific explanation that was advanced by mid-twentieth-century logical positivists and was championed as an ideal by some archaeologists during the early days of processual archaeology in the 1960s. The two should not be confused, however: While the deductive-nomological model requires invocation of “covering laws” of nature (or culture), hypothetico-deductive thought experiments make no appeals to laws of any sort. They pertain instead strictly to local archaeological contexts, as do the explanatory hypotheses that emerge from them.

Parsimonious explanations, that is, explanations that rest on a minimum of assumptions, are intuitively more appealing than explanations that invoke a greater number of assumptions. In line with its intuitive appeal, in archaeology parsimony is invoked with remarkable frequency in support of one’s favorite explanation. Caution is needed, however: Archaeologists often use the adjective “parsimonious” in lieu of “plausible” or “satisfactory,” while “parsimonious” is at best a synonym of “economical” and “simple,” so that “the most parsimonious explanation” is in fact the simplest explanation (i.e., the explanation that depends on the least number of assumptions). In such cases, it is not clear that one’s favorite explanation is indeed the simplest of a set of rival explanations, nor is it clear that its alleged parsimony makes it more probable than the other explanations in the set. The main merit of a parsimonious and elegantly articulated hypothesis is their perspicuousness. But perspicuousness is a pragmatic virtue, not necessarily an epistemic

one; it does not by itself render a hypothesis more likely than rival hypotheses. In conclusion, it makes sense to bring parsimoniousness into the discussion *only* where two or more hypotheses explain the same set of observations equally well. Even in that case, parsimony and elegance of articulation can be thought of as methodological devices, not necessarily as justifications for ontological commitments.

Abduction in archaeology is by no means a value-free process. Entrenched beliefs about the moral order of the social universe, but also prestigious, broadly shared theories may limit the range of explanatory options in a given case by strongly favoring options compatible with themselves. The epistemic effects of such biases on the archaeologist’s inferences are by no means negligible (let alone their political consequences; see SCIENCE AND POLITICS). African archaeology of the colonial era, when Africans were believed to be incapable of self-improvement and all innovations in the continent had to be the work of colonists from elsewhere, is a well-known case in point. Comparable, if more muted, biases can interfere with archaeological inferences in the present as well. But today’s archaeology is characterized by an unprecedented plurality of voices and critical points of view, as well as by a fast pace of publication. In these conditions, biased inferences do not remain undetected for too long and their faults are critically appraised soon after they are published. Whether the future will be like the present in this respect is not clear.

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Making and Skill

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Making

On the strength of the Cartesian view that divides the world into nature and culture, the process of “making” is commonly considered to transform a natural material into a cultural object, an artifact. Practitioners hereby impose their desired mental design template upon the material world. In contrast, Ingold (1998) has advocated a “dwelling perspective” whereby the process of making is actually a process of growth in which maker, material, and the environment engage in an ever fluid and responsive act of co-creation. The form thus emerges out of the process of engagement or improvised journey, rather than being predetermined by an outside force. Practitioners themselves often refer to this intimate dialogue with the material as “feeling” (Keller and Keller 1996) and consider the material they work with as “alive.”

While tools are often utilized when “making” objects, it is our own bodies that are the original tools. On the one hand, the human body is a biological entity that functions in accordance with biological, anatomical, physiological, and neurological rules. Thus the way it interacts with its environment and with matter is broadly predictable and, some scholars would argue, almost preprogrammed. On the other hand, people learn to use their bodies in accordance with the customs of their society, and thus the body is an inherently cultural object whose movements and motor habits vary by age, sex, and class and from society to society. Instead of being *either* an exclusively biological *or* a social entity, the body is actually a biological, psychological, and social nexus—or, as Mauss would call it, an *homme total*. Culture-specific body styles such as walking, eating, or swimming are what Mauss has called *techniques du corps* (“techniques of the body”; see Mauss in Schlanger 2006).

While broadly in agreement, Ingold (1998) critiques Mauss for arguing that body techniques are acquired *from* a social setting, as if the environment contained a preconstituted concept of what is to be learned and as if that knowledge simply needed to be transmitted from one generation to the next. Instead, Ingold believes that nothing is transmitted just by itself but learning takes place *within* a social and environmental context, through a process of guided rediscovery. Acquired skills are seamlessly weaving together biology, evolution, and history as individuals grow up in their society. While focused more on environmental aspects, Ingold acknowledges the contribution of Gibson’s (1979) theory of affordances to his own thinking. Gibson’s ecological approach holds that motor habits are not being passed down as existing mental templates but emerge in a dynamic interaction between organism, environment, and task.

Ingold’s view is also related to Bourdieu’s concept of *habitus*. *Habitus* is a system of embodied dispositions that organize practices, thoughts, perceptions, and actions across a given group. The practices that constitute a *habitus* simultaneously reflect and reproduce a group’s or individual’s social history. “*Habitus*—embodied history, internalized as a second nature”—has a harmonizing effect; as individuals are socialized into their group, *habitus* is ever adapting and cannot be predicted (Bourdieu 1980: 56). These dispositions and practices are commonly shared and understood by members of the group and imbued with meaning, though this knowledge is not always declarative. *Habitus* relates to body postures or mannerisms as much as to mental classifications, feelings, and actions.

To the outside observer, the process that practitioners undergo as they make things appears to follow a linear sequence, which flows logically and uninterrupted from the beginning to the end of the making of an object. This idealized process is encapsulated in the term *chaîne opératoire* (operational sequence or chain). Introduced by Leroi-Gourhan ([1964] 1993), this methodology allows scholars to describe the step-by-step construction, use, and discard of

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objects in chronological, spatial, technical, and sociosymbolic terms. Knowledge of all these aspects allows a structured, multifaceted understanding of practitioners, their craft, and the sociocultural context.

In reality, however, the act of making is neither linear nor necessarily fully thought through at the beginning. Producers usually have an “umbrella plan”—a concept of what they would like to produce and a skills set with which to achieve it. Interviews with practitioners have shown, however, that these ideas are often rather vague, with implications of actions and alternatives loosely interconnected and open-ended (Keller and Keller 1996). Practitioners experience the process of creation as a complex continuing reciprocal feedback loop as they compare the mental image with the actual reality, monitor their progress, diagnose problems, and apply corrective strategies. As the process unfolds, aspects that were important at the beginning fade away, to yield to entirely different features that are essential to a successful completion. Much of the manufacturing process and of the knowledge used in it are tacit, spontaneous, and automatic—what Schön (1983) has called “knowing-in-practice”—though it is particularly at points of failure that practitioners engage in more conscious reflection, revision, and correction.

Often practitioners across a domain develop a shared understanding of how tasks are to be done. Lave and Wenger (1991) have called groups that have a common interest in a subject, idea, or activity “communities of practice.” Communities of practice are united through the sharing of daily practice, learning, teaching, and knowledge that foster a common identity and meaning among members. This shared enterprise may be explicit, codified, and insitutionalized, but more frequently it is tacit, assumed, and embodied. Whether explicit or implicit, the resulting outcome of this common experience will be a shared repertoire of motor habits, styles, stories, tools, actions, and concepts.

As with the distinction between arts and crafts, scholarship traditionally separates between mind and body, assigning greater value to the former. When considering theories of learning, this mind–body dichotomy is most commonly expressed in a distinction between “knowledge” and “know-how.” Knowledge (*connaissance*) is

a mental representation of the object or process that can be passed on by means of words. By contrast, know-how (*savoir-faire*) is experiential learning that can only be acquired through doing. Knowledge is assumed to precede the know-how, since manufacture first requires a design. However, Ingold has persistently argued that one cannot separate the mental from the physical. Concepts and techniques can be communicated verbally and demonstrated physically. However, they cannot be taught as such. True knowledge and expertise can only be acquired through practice alone. Thus knowledge cannot be transmitted from generation to generation, but always has to be learned through practice: “the only way one can really know things... is through a process of self-discovery” (Ingold 2013: 1). This process requires the learner to physically practice the skill s/he wish to acquire. Practitioners have to gain experience in how something feels, looks, or sounds. This process of engaging practically with one’s craft is what Gibson (1979) has called an “education of attention,” also known as “understanding in practice.” Enskillment is hereby understood as learning by doing within the sociocultural context of the task.

Skill

According to Fitts (1964), skill acquisition falls into three stages of development: *cognitive*, *associative*, and *autonomous*. In the initial, cognitive phase individuals learn the fundamental structure of an activity. They are focused on learning how to execute the individual tasks and often can get lost in the detail (“tunnel vision”), but do not yet have an understanding of how these steps link together temporally or relate to the overall task goal. Tasks require great concentration, and mistakes are frequent. Feedback is essential in order to correct mistakes and misunderstandings. With repeated practice in the second, associative phase, learners gradually acquire the necessary individual skills and are able to execute tasks without gross errors. At this stage, learners are able to “chunk” activities into larger, meaningful segments, which can be completed more quickly and efficiently; and they develop a temporal understanding of the overall task sequence. An

understanding of how skills are connected to create the greater conceptual whole is now being developed. In the final, autonomous phase, performance has reached a stable and consistent level and the execution of activities has become almost automatic. Practitioners can now achieve a satisfactory level of performance effortlessly and rapidly. For most habitual everyday activities, it can take as little as 50–100 hours of training and experience to reach this level of competence. Research into typing and language acquisition has shown that competences, once gained, deteriorate only slowly and can be reacquired rapidly, even if a practitioner had ceased practice.

Feedback is essential if a learner is to improve. It can be verbal, physical, or both. Research has shown that a combination of verbal and physical instruction leads to the fastest improvements in the learner. This is often undertaken in a hierarchical sequence in which low-level skills are gradually combined into higher skills. When a teacher completes more difficult tasks that are beyond the skill level of an unassisted learner in order to allow that learner to achieve the final goal, the process is called “scaffolding.” That learning is an innately social activity is captured by Vygotsky’s (1976) concept of the “zone of proximal development,” where a child initially observes the teacher and then, over time, comes to work alongside him/her until s/he has mastered the task in its entirety. Lave and Wenger’s (1991) model of “situated peripheral learning” also places focus on how learning is more than task-specific skill acquisition; rather it includes the acquisition of social values and attitudes within which the skill is practiced. The knowledge of body techniques increases with age, as children observe and copy adults and internalize culturally appropriate behavior. Non-native learners, by contrast, are at a disadvantage because they, in effect, have to acquire two sets of skills. They will often require explicit instruction in order to learn how to move and position their bodies.

Following Ingold (1998), it is important to emphasize that skill is not something that can simply be passed on, like a formula or a set of rules, but has to be acquired by each individual, in a process of guided rediscovery that allows learners to grow them into advanced skills, to get a “feel.” Likewise, skill acquisition is biological

growth inasmuch as it is cultural growth, because the practitioner’s neurology, musculature, and anatomy change alongside his/her understanding of the cultural role and relevance of the skill.

Often practitioners are content with achieving an acceptable level of competence, though a few are sufficiently motivated to achieve the highest level of skill possible. Experts are individuals who have built up a large repertoire of possible actions and remedial interventions that are specific to their domain and that they can apply quickly and fluently to new situations and changing conditions as they actively monitor their performance. Thus expert performance is the exact opposite of automated or intuitive motor skills, or what Bourdieu has called “learned ignorance.” Research into chess, sports, medicine, computing, and music has shown that these outstanding perceptual, physiological, and cognitive capacities are not genetic, but acquired as a result of around ten years (or ca. 10,000 hours) of *deliberate* practice in a given domain (Ericsson, Krampe, and Tesch-Römer 1993). Deliberate practice has a different quality from regular mechanical activities in that it is reflective and targeted explicitly at improving specific aspects of an individual’s performance. It is most successful when there is immediate feedback and there are opportunities for repetition until the set goal has been achieved. Because deliberate practice is hard work and not inherently enjoyable, practitioners must be highly motivated and have an ability to concentrate fully, for up to four hours a day, when aiming to improve their performance. A high level of expertise in a particular domain is often sustained into old age, although normal age-related decline is apparent in unrelated activities.

SEE ALSO: Archaeologies of Technology; Creativity; Mind and Cognition; Substances and Materials

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Material Agency

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Material agency denotes the possibility that things can act. The defining criterion for such agency has varied between theoretical strands, but generally entails the notion that material objects have an effect on the course of action that is irreducible to direct human intervention. The concept of material agency is part of the “material turn” that puts objects in the picture of the humanities and social sciences as more than simply passive instruments or empty shells for social symbols and meanings. It contributes to a broader challenging of the boundaries between ontological categories such as nature and culture, active and passive, or persons and things, and opens new opportunities for collaboration between scientific and interpretive archaeologies.

Relational agency

The notion of agency is an enduring legacy of post-processual archaeology. Moving away from New Archaeology’s template of people as survival- or profit-seekers, and infused with practice theory, post-processualism’s agency denoted people’s differential capacity to act, steered by their structural position, but allowing for the spark of contingency and improvisation. Gender, power, class, and so on were therefore no longer qualities that one possessed (as per New Archaeology), but emerged out of the constant, dialectical recomposition of social structure in daily practice and were inherently relational.

Post-processualism revolutionized archaeology’s take on human agency, but did not extend this to the object world. An interest in things as symbols (see MATERIAL SYMBOLS) was soon transformed into a broadly textual reading of material culture, emphasizing how things could be ascribed different meanings depending on

context. But not only are things unlike texts in many ways (see MATERIAL CULTURE); a hermeneutic model of “reading” material culture placed meaning and agency strictly in the human realm, far removed from things. Attributed meaning(s) by people, things themselves became passive signifiers in a semiotic play, defined by their arbitrary, contextual relation to other things, but not by their physicality, shape, or properties.

The material turn in the humanities and social sciences has invalidated this strict division between humans and things, between the social and the material. Ethnographers described how these divisions do not hold up in other societies, where there can be a fluidity between people, animals, and things, as in Andean cosmologies according to which the earth could solicit offerings or mountain tops could be revered as ancestors. Only in the last decades have anthropologists started taking these descriptions seriously as alternative ontologies, instead of merely classifying them as “premodern,” that is, on their way to transforming into a modern set of principles predicated upon a nature/culture duality. Meanwhile, ethnographers of science have muddled the supposed purity of the modernist scheme itself, by showing how scientific facts—the epitome of western immaterial rationality and its Enlightenment principles—rather than deriving from purely abstract eternal laws, are contingent upon such things as the size of test tubes, the distribution of funding, and the focus of gossip (see HISTORY AND SOCIOLOGY OF SCIENCE). This is not to say that science is untrue or unfalsifiable; it is rather to specify that its validity is built on foundations of a different nature and reach than previously imagined.

As the ontological fences were pulled down both by comparative anthropology and by close analysis of the western model, things and people started encroaching upon one another (see PERSONHOOD AND OBJECTHOOD). Things could be constitutive parts of persons, with cyborgs as the most evocative example. Conversely, people could not be truly social, or even human, without things: objects structure social interactions, and

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enable many of the activities that make us human, such as writing, thinking, trading, and so on. But whether that means that things have agency and what this agency looks like is answered differently in different theoretical traditions.

Relational agency and the material turn

If agency is considered as something one possesses, then things tend to be denied agency. There does not seem to be something inherent to things that can make them act: things only act under certain circumstances, as part of particular assemblages, in specific settings. Material agency enters the agenda—implicitly or explicitly—only when the model of agency adopted is relational, situational, and dialectic. A first set of studies allow objects to contribute to action but refuse to label this as “material agency.”

Daniel Miller was one of the first to create conceptual space for things within a post-processual (or more broadly post-structuralist) framework of agency. According to Miller (2010), people come to understand who they are and what their position in relation to others is through producing and using things, a process termed objectification, nodding both to Marxist materialism and Bourdieu’s practice theory. Miller’s work has spawned a plethora of studies on consumption practices, taking as their object modernity across the globe: from blue jeans, over saris, to Coca-Cola. Objects feature in a humble yet important role, not only as the products or means of action, but also giving meaning and sense to those actions and their human agents. Yet material agency properly speaking remains dormant: things are either tools for (instrumental) or signalers of (representational) meaning. Miller’s model has sometimes been referred to as “materiality,” which has also, however, become a catch-all phrase for “objects.”

Recent phenomenological and cognitive archaeologies carry similar concerns of human perception and identity forward, but on a smaller scale. Phenomenology is one of the rare philosophical traditions of the twentieth century to have explicitly theorized the relation between humans and things. Heidegger’s tool analysis discussed how objects in our daily encounters

retreat into a kind of objectness in excess of human knowledge (ready-to-hand). The famous example of the hammer illustrates that this is only one possible mode in which people engage with the world: Only when hitting one’s hand instead of the nail does one realize that the hammer is really hard, solid, made of heavy stone, and capable of hurting (present-at-hand). Husserl similarly showed that our prime mode of apprehending the world is not that of scientific abstraction: When encountering a chair, for example, the chair can strike one as hard, comfortable, high enough to sit at a table, and so on, but not as “50 cm wide and made of polymers.” Others, like Merleau-Ponty, shifted emphasis to the human senses, which remained rather abstract in Heidegger’s accounts of human–thing encounters.

While phenomenology’s philosophical basis is firmly anthropocentric, it has provided fruitful grounds for the material turn. Philosophers and anthropologists of technology have built on phenomenology to demonstrate the inextricability of humans and things in the process of perception. Thermometers, for instance, actively make temperature readable and understandable to us—one might wonder how the notion of temperature would be different without them. And some people simply cannot see without glasses or contact lenses. These examples demonstrate the close collaboration of things in perception and experience, but things’ role can still be argued to be no more than a product of human instrumentalism.

The emphasis on perception and mediation puts this body of work in close conversation with recent cognitive studies that are moving away from a Cartesian tradition of studying the brain as a closed container, divorced from body and world. While phenomenology had initially been introduced in archaeology with post-processualism, cognitive archaeology was an offshoot of the processual tradition, as for example in Colin Renfrew’s theory (2001) that material symbols do not passively refer to pre-existing concepts, but instead were crucial in bringing new concepts (e.g., weight) into existence in human evolution. This illustrates how the material turn has helped make the old paradigmatic landscape of archaeology obsolete.

The body has emerged as a productive nexus for these issues of perception (see PERCEPTION

AND EXPERIENCE) and cognition (see MIND AND COGNITION), and has spurred another related branch of phenomenologically inspired studies on skill (see MAKING AND SKILL). Anthropologist Tim Ingold's work has been particularly influential in archaeology. His iconic example is that of weaving a basket: When one weaves a basket, one is not simply imposing a predefined mental design on passive matter. Instead, the shape of the twigs, their relative flexibility, their thickness, and so on, will all work together with one's hands and experience to produce the final form of the basket. In archaeology, this has provided a productive lens on crafts and embodied learning. While things—twigs and clay—have an effect on the course of action that is irreducible to outside forces, Ingold sees material agency as a reductive take on what is a constant flow of agency as more generic life forces across “meshworks” which can crystallize into stable forms, but only ever temporarily.

In all of the above strands, things contribute something to action that emerges in their relationship with humans. But whether for fear of losing humanity out of sight, or because of analytical strategy, humans remain the cornerstone of analysis and causality, and the term “material agency” is shunned.

Material agency

When “material agency” was coined as a term, it was in many ways no more than a rhetorical labeling of a concept that was already emerging in the material turn. Nevertheless, it generated shock waves within a long western tradition of human exceptionalism that is built into the moral, theological, legal, and social apparatus of contemporary society. In dissecting material agency per se, the below strands are less concerned with the minutiae of perception, skill, and material engagement than with causal effect.

Alfred Gell's *Art and Agency* (1998) breaks down sequences of actions into chains of cause and effect. The painting of a portrait, for instance, is not reducible to the intention of the painter and its translation to the passive matter of paint and canvas. Instead, the painter's intention is triggered by another art work or visual form. In

a similar vein, an art work can have a profound effect on its viewer, who is led to attribute agency to it deriving from the artist and the chain of precedents. As such, things are folded into causal chains whose driving force, however, still lies squarely with human action. The mechanical overtone of some of Gell's schemes of cause and effect—called *gellograms*—is the result of his reacting against the dominance of aesthetics in the anthropology of art at the time.

Aside from Gell's rethinking of the scheme of action and influence in art, he also offered a vivid reading of the human habit of anthropomorphizing objects. In defiance of our western ontology and its strict division between the material and the social worlds, we catch ourselves speaking to devices such as our cars, giving them names, and even attributing feelings to them. Gell remains firmly within western ontology, however, ascribing this anthropomorphizing phenomenon to a fallacy of human thought. While Gell created an opening for a material agency predicated upon causal effect, his work testifies to a continued struggle with anthropocentric models of agency.

The other framework that explicitly embraces an effect-based material agency is Actor-Network Theory (ANT). ANT originates in the social study of science and embraces a flat ontology as method by not a priori positing ontological parameters (e.g., active subjects, passive objects). Its proponents include Michel Callon, John Law, and Bruno Latour, and the latter in particular has provided a set of iconic examples perused in archaeology, such as the European hotel key. Latour (1991) explains the presence of key weights as the result of hotel managers trying to persuade their customers to leave their keys at the lobby desk when exiting the hotel. The key weight succeeds where oral and written requests failed precisely because of its material specificities—its size and weight. While at first glance the key weights may seem to be used instrumentally, to satisfy a human purpose, this does not capture their role fully: without the weights, this kind of action—persuading guests to leave their keys—would simply not have been possible. In the course of this process, the keys are no longer mere “keys” but have been transformed into something that is easier repeatedly picked up from the desk than carried around all day. In archaeology, ANT

has proven useful not just for rethinking the practices involved in the generation of archaeological knowledge (see *SYMMETRICAL ARCHAEOLOGY*), but also in understanding the creation of archaeological types, and in recasting actors and causes in large-scale historical narratives (Van Oyen 2016).

The most recent take on material agency to have been adopted in archaeology is assemblage theory, combining elements of ANT's radical ontological position with a notion of organic flows akin to Ingold and some of the phenomenological tradition. Gilles Deleuze is its main proponent, but in the meantime, assemblage theory has become a motley assortment of approaches, associated with theorists such as Manuel DeLanda and Jane Bennett (see *NEW MATERIALISMS*). All share a view of agency as distributed across heterogeneous assemblages, whose sum is greater than their parts. Assemblage theory holds particular attraction for archaeologists, because of its promise of accommodating scalar transitions; its emphasis on temporality as flows; and its affinity with archaeology's stock vocabulary of the "assemblage" (see *ASSEMBLAGE*).

The future of material agency

In sum: Things can have agency, but only if agency is seen as an emergent and relational phenomenon and not as an essential property; and this material agency is not just like that of humans. The most human-like material agency actually appears in those frameworks leaving least space for material agency, such as Gell's anthropomorphism. This is important to emphasize, as criticism of material agency and hesitation to adopt the term (as per the first set of approaches discussed) are rooted in a moral concern about equating things with humans. If not people, but guns, kill people (with Latour), then where does moral responsibility reside? While material agency does complicate the picture of causality and, therefore, morality, none of the frameworks above ascribes capacities of intentionality, reflexivity, and consciousness to things. Guns don't kill people *of their own decision*, but they nevertheless contribute an irreducible element to the final outcome of action. In that regard, John Robb (2010) distinguishes between a conscious

agency (why?), restricted to human agents, and an effective agency (how?), which is distributed and not a priori limited to certain ontological categories. In the end, then, the different versions of material agency are unwilling to abandon a western ontology. This is where the material turn diverges from the ontological turn.

While the moral and legal implications of taking relational agency seriously need thinking through, so does the model of causality that archaeology uses to write history from things. Things' agency is an effective, although not a determining, agency. It does not entirely discredit humans as the ultimate drivers of action, but it cannot exist but in a model of relational and emergent causality. This changes the configuration of possible answers to questions of "who" and "why." Ultimately, material agency may harbor its own obsolescence: As we grapple with the interpretive challenges it posits to the boundaries between humans and things, we may find that we are left not with things acting, but with different varieties of relationality and the challenge of characterizing those.

Material agency and archaeological sciences

Among the many unresolved issues surrounding material agency, three in particular hold promise for archaeological sciences, as already intuited by Andrew Jones (2004).

First, one type of critique from within the material turn, for instance by Ingold (2007), cautions against the under-theorization of material properties (see *SUBSTANCES AND MATERIALS*). In investigating just how the physical stuff of things contributes to their social effects, archaeological sciences can claim an important stake. Archaeology has a long tradition of attributing social and historical change to material revolutions, as in epoch-making transitions such as the Bronze Age. Material analysis, in turn, is foundational to archaeological sciences. More and more case studies detail the social dynamics of material properties, but these have not yet been abstracted to refine conceptualization of human–thing relations.

Second, how to project material agency in time? Through the analysis of provenance, recycling, and use wear, archaeological sciences have been instrumental in charting artifact biographies. But these are emphatically anthropocentric, modeling artifacts as having human life courses, and defining these with reference to external regimes of value. Ian Hodder's (2012) version of entanglement (see MATERIAL ENTANGLEMENT) instead shifts attention to the practical demands that things make on humans, drawing them into a bind of dependency, which has a temporal logic to it. Alternatives such as trajectories and genealogies can account for the unfolding of the social logic of broader classes of artifacts and their stylistic and material links. The challenge is not to portray matter as an inert substrate to the external changes undergone by objects.

Finally, the interpretive implications of material agency beg the question of how to marry the very grounding of archaeological sciences in the modernist ontological divide between nature and culture and its concomitant linear view of cause and effect with a big-picture emergent causality.

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FURTHER READINGS

Material Culture

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Archaeology and material culture

Material culture lies at the core of the archaeological endeavor to understand past and present societies. It is archaeology's precondition—if archaeology did not have material culture, it would have nothing to work with: no houses, no streets, no statues, no potsherds, no grinding stones. The past—and more recently also the present—is studied through the material remains of human activities, relations, and existential conditions, as traces and evidence of a wide range of topics. From very early on in the development of archaeology as an academic discipline, material culture has been the medium through which past human societies could be understood. Famously, Christian Jürgensen Thomsen (1788–1865) defined the Three-Age system on the basis of distinct materials of artifacts belonging to different periods. In the nineteenth century, material culture was the token of the evolutionary stage of the people behind the artifacts. The collection of Augustus Pitt Rivers (1827–1900), at the University of Oxford, founded in 1884, is a prominent example of this. The collection attempts to show the progress of human civilization, where simple artifacts are seen as a token of simple organization, while complex design marks complex societies. These are examples of how archaeology (and anthropology) has used material culture as a prism for understanding societies in the past and the present.

Yet, what constitutes material culture has nevertheless not always been agreed upon by archaeologists and anthropologists, and is constantly subject to differing uses and much debate. Material culture has been distinguished

in a number of ways, ranging from being synonymous with “physicality”—for example, a basalt statue—to being defined as the “sociality of things”—that is, as manifestations of cultural meanings through fabrication of material objects. A related concept is that of materiality, which may be described as the social constitution of self and society through things (Preucel 2006). Material culture is sometimes a collective denominator for a plethora of related terms and phenomena: technology, objects, artifacts, things, matter, aggregates, tools, stuff; each dominating another according to historical context or theoretical approach. For instance, Dan Hicks (2010) has argued that the term *material culture* only came to dominate after World War I, as an alternative to *technology*. Some scholars choose to define their terminology rigidly and distinguish clearly between, for example, artifacts and technology, while others opt for colloquialisms such as *stuff*, or use the term *material culture* without further theorization to denote something produced by humans. In this sense, material culture (e.g., a house) can be seen as in opposition to nature (e.g., a mountain). Yet such distinctions are often untenable. A hot-air balloon may be a case in point: People make the cloth (material culture), but it capsules air (nature), heated by fire (nature), ignited by people (material culture), all of which is transported by the wind (nature). Which part is material culture, and which is not, seems hard to distinguish. James Deetz (1977, 24–25) also noticed this when suggesting that even the way beef is cut is material culture, as it captures the cultural logics of what counts as ribs, tenderloin, sirloin, and so forth.

Most recent publications refer to material culture as a broad generic term, though, synonymous with archaeology's “matter.” So, while definitions are difficult and can be subject to debate, it is important to observe that “material culture” is composed of “material” and “culture.” This implies that culture is not necessarily material, and that archaeology is preoccupied with a particular dimension or expression of culture. It also indicates that not all material can necessarily be considered culture, and that

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material culture refers to something made by, manipulated by, or reflected upon by humans. In recent discussions, anthropologist Tim Ingold (2007), in particular, criticizes the term *material culture*, as well as *materiality*, for divorcing “the material” from “the mind” (culture) as somehow hovering over things, rather than being integral in its continuous formation. Such critique is not lessened when terms such as *materiality*, which in other disciplines is considered to be raw unsocialized matter, is understood in some recent archaeology and anthropology to be inherently social (Miller 2005). There is no distinction between the social and the material, which is also what the combination of “material” and “culture” signifies to parts of the archaeological environment.

This terminological plurality is also reflected in curricula at universities, where courses in “material culture” can refer to different teaching outcomes. At some institutions, a course in material culture may build up empirical knowledge of the artifacts from a specific period (e.g., a comprehensive overview of Neolithic artifacts in southern Scandinavia), or offer an introduction to various classes of artifacts (e.g., flint, ceramics, or glass). In other educational institutions, a course in material culture might revolve around theoretical perspectives on material culture as a means of understanding societies and relations in the past (e.g., to understanding power, gender, rituals, or economy). Material culture may thus refer to rather different fields of knowledge and to disparate academic frameworks for understanding archaeological sources.

Hence, material culture in archaeology has two roles: First, it works as primary archaeological source material; it is the stuff through which archaeologists can access knowledge of the past. And second, it works as a medium for social relations; it is one of the media through which people forge relations, negotiate power, and construct their identities. The first of these roles implies that material culture is archaeology’s data, and the second indicates that these data need to be processed in order to constitute knowledge of the past in meaningful ways.

The social role of things

The latter role of material culture—its capacity for constituting relations between people, whose bodies may itself be seen as material culture, and between people and the material world—has been the primary focus of attention in archaeology since the mid-late twentieth century. Walter Taylor (1913–97), for instance, argued that culture was not observable to archaeology directly, because culture was located in the mind, yet material culture is the product of culture, available to archaeological scrutiny. A number of archaeologists also became concerned with how the relationship between culture and artifacts was to be understood, and wanted to understand the structuring effects of material culture in the development of a certain cultural behavior. This led to the proposition that artifact design, and the use and distribution of artifacts, could be seen as patterned, and that the pattern reflected a given cultural behavior: the socialization and implicit cultural norms behind the archaeological assemblages. For James Deetz (1930–2000), it was important to observe how these patterns changed over time, and how they could be traced archaeologically. Lewis Binford (1930–2011) famously defined culture as the extra-somatic means of adaptation, which means that material culture is basically a means of survival for the human organism. However, he dismissed the idea that archaeology had the objective of studying the relations between human behavior and material culture, since he maintained that the archaeological record does not hold any direct information on that topic. Binford argued that the cultural “system” producing the archaeological record was fundamentally different from the record itself: There is, in other words, no *direct* correlation between excavated material culture and the society originally producing these artifacts. Instead, archaeological assemblages had to be correlated with comparative uses and distributions of artifacts in living, “dynamic” contexts in order to unlock the archaeological record. Binford also argued for an empiricist and quantitative research design, which was mirrored by other influential scholars of his time, such as David Clarke (1937–76) and Colin Renfrew (born 1937), both at the University of Cambridge.

Along these lines of research, Renfrew has been a key proponent of the pursuit of a cognitive archaeology to study the relationship between the human brain and behavior through skeletal evidence and material culture.

Archaeological redirection formed in Cambridge as a response to the positivist and scientific agenda of the above approaches to archaeology and material culture. This has marked the beginning of the most dominant approaches to the study of material culture in recent years, building on the work of Ian Hodder (born 1948) and the so-called Cambridge School in the early 1980s. This agenda has also been called “the material culture turn” or “the material turn.” This approach revolves around understanding the *active* nature of things in social life. That is, objects do not merely *reflect*, but help *constitute* identity, power, gender, and so on. Hodder wanted to understand the continuously changing role of things and the symbolic meanings they carried. He and his students thus explored the potential of understanding the active role of material culture in human life, including ethnoarchaeological studies in the present. The ambition to explore identity and power through material culture was in part represented by the development of a distinct gender archaeology. The focus on gender provided a framework for examining the relationships between body, embodiment, identity, and the engendering of material culture. Moreover, this included important steps in the direction of analyzing not only the ways in which objects are associated with gender, but also how gender is shaped through material and corporeal performances.

This intellectual background, along with many of the students graduating, led to the formation of a more disciplinary independent approach to material culture, which in the British context, in particular, centered on Daniel Miller (born 1954) and Christopher Tilley moving from Cambridge to the anthropology department at University College London (UCL). Miller and Tilley focused on what Miller calls “processes of objectification,” where the key point is that people continuously shape their values and meanings through material culture, which in turn shapes their lives. Even the things we rarely notice are part of processes of constituting social worlds by acting in the background, not as separate reflections of said

values, but in a constant dialectic between subject and object. Key topics here have been the practices that people do with objects, how things are transferred from a market sphere to a personal sphere, and how phenomenological perspectives on things may open new understandings of the role of things.

Another simultaneous discussion was seen in a focus on “the biography of things” in the wake of Igor Kopytoff’s (1930–2013) article in the influential volume *The Social Life of Things* (Appadurai 1986). Here, objects, like people, are shaped by the history of use and meanings they have taken part in, and thus, like people, must be understood through a biographical lens. An object is, thus, not just an object, but is formed by the relation of which it is a part. A product of this more general call to understanding material culture as an essential part, rather than merely a passive product, of social life, is the cross-disciplinary *Journal of Material Culture* emerging from the UCL research environment.

As indicated above, much of the discussion of material culture in archaeology is found in its dialogue with anthropology. One such example is the heated debate at the turn of the twenty-first century around what Alfred Gell (1945–97) calls “the agency of things” (Gell 1998). Here material culture is seen as an agent in social lives, although not with the same capacities as humans. A marked shift here, which is still intensely debated, is the switch from seeing agency as resting on *intentionality*, where material culture cannot choose to do otherwise, as humans can, to *causality*, where agency is what causes an event to happen. For instance, it is the agency of the flames that makes a house burn. But there may be multiple agencies involved in the process, depending on whether it was lighting it that made the fire to begin with, or a person lighting matches who ignited a material that fell on another highly inflammable object that then set the house on fire. In such discussions, we thus see, in the most profound way, the distinction between material culture as the (passive) outcome of human practices and the (active) role that objects, whether tangible or intangible, play in human practices.

Although covering many different perspectives, the most dominant branches of material culture studies originated in the 1980s, in what might, in hindsight, be dubbed, respectively,

the Cambridge School and the UCL School. It may not be entirely unjustified to speak of the recently formed “Stanford School,” which is largely synonymous with so-called symmetrical archaeology. Symmetrical archaeology was largely formed as a critique of modernist “bifurcations,” that is, the perceived dualisms between humans and objects, nature and culture, and past and present. Scholars such as Michael Shanks, Christopher Witmore, Timothy Webmoor, and Bjørnar Olson (2012) argue that archaeology is fundamentally *the* discipline of things. They borrow their vocabulary from anthropologist Bruno Latour, and speak of the “infiltration” of humans and nonhumans, which means that humans are not distinguished as being of primary importance in the archaeological endeavor. Instead, the human is de-centered and assumes a position as a phenomenon among many other heterogeneous phenomena. Rather than speaking of material culture, these scholars furthermore choose to orient their terminology towards “things” or simply “nonhumans.” In this, they draw on the notion in Martin Heidegger’s philosophy of the *thing* as etymologically coming from the verb *to gather*. This implies that things have the capacity to constitute gatherings of a variety of phenomena: social meaning, identity, function, symbolic value, and so forth. In this capacity, symmetrical archaeologists argue that we need to see humans and nonhumans as a continuity that should not be parceled out rigidly, because even though people and things are different (as are all people and all things), they are not oppositions. We have thus, since the 1980s, seen a strong move to redefine the term *material culture*, or simply shift to another word, such as *things* or *materiality*, even turning back to *technology*, the word that predominated in the nineteenth century.

Future directions

The embedded nature of material culture and human lives is now evident, and the necessity for interdisciplinary collaboration to explore such entanglement has proven its point in archaeology. Although the ever-increasing new methods to understand aspects of material culture offered by natural sciences have prevailed, so too have theories from disciplines such as anthropology,

geography, design, sociology, and art history shown their value in understanding what things mean, do, and symbolize, questions that have framed material culture since the 1980s.

To highlight some trends we see expanding at the time of writing, it is first clear that the advances made in natural sciences and technology will undoubtedly shape the future of understanding material culture, and the social worlds it has constituted in the past. While the specific questions asked often say more about the contemporary period than the past, ancient DNA studies have, for instance, allowed for new insights into the demographic composition of regions, and hence also highlight trade routes and innovation processes shaping material forms. In archaeological topics like these, we see a pivotal role in bringing science and archaeology closer together. Likewise, the use of drones and digital maps has expanded the possibilities of finding new locations and areas of ancient cities that have hitherto gone unnoticed. In essence, such techniques allow us to understand broader global issues of origins and the movement of people, things, and ideas, while also democratizing the exploration of material culture to encompass both highly specialized DNA scientists and amateur drone users and Internet explorers. Simultaneously, isotope analysis, micromorphology, use-wear analysis, and other such techniques offer insight into everyday life, perhaps even individual life stories, in combination with DNA records, of people long past. In other words, with the developments in new technologies and material sciences, we are able to correct previous knowledge by asking new questions of the material remains about human origins, organization, and spread.

Second, archaeology, beyond the exploration of the past, offers a critical perspective on the present. This is particularly achieved through the increasing focus in archaeology on dissolving radical distinctions between past and present in intellectual currents such as “critical heritage studies,” exploring the political entanglement of places and past material culture in the present. In such a context, the role of archaeologists—to engage with popular or alternative conceptions and imagery about the past, as unfolding through material remains—is pertinent, although still in pressing need of more intellectual and theoretical

debate. Archaeology and the study of material culture thus has become an increasingly intellectual endeavor as much as an exploration of the past. It appears that while academic careers are often made from excavating new locations, it is important also to more actively engage with both the publication and interpretation of earlier finds, not least in the way they play a role in contemporary heritage politics (Smith 2006; Harrison 2013).

Finally, the limits of relying on available material culture have become evident. Not only are archaeologists often left with very little material to make claims from, often there is actually a socially productive deliberate avoidance of things either on individual, community, or political scale—incandescent light bulb and smoke bans are contemporary examples. For instance, as Severin Fowles (2010) illustrates, taboos as well as restrictive consumption ideas may foster a lack of material culture, which is central to an understanding of said past society. One strand of future directions may thus point towards exploring how and why things are or become absent. Parallel to this is also the fact that people's sensory experience is shaped by intangible material culture, such as light, smell, and temperature, or by other less tangible material forms, which are only more recently being investigated as a form of material culture (Bille and Sørensen 2007; McFadyen 2010).

SEE ALSO: Archaeology and the Present; Assemblage; Drones; Genomics: Ancient; Heritage and Politics; Material Agency; Positivism; Symmetrical Archaeology

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Material Entanglement

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Colloquially the word entanglement is used with many inflections of meaning. Dictionary definitions usually refer to a mass of confusedly interlaced or intertwined threads or strands, knotted or coiled together. People talk of being snared in entanglements that are complicated, unfortunate, or obstructing. Entanglements seem like jumbles that are difficult to sort out.

For example, US relations with China are described as entangled because on the one hand the United States and China want to reach agreement on climate change (for a whole set of perhaps quite divergent reasons) and yet they strongly disagree on human rights, on technology copyright, on hacking, and so on. So a key idea is that entanglement involves contradictions. The latter cannot be described in terms of positive and negative feedback, and they cannot be reduced to Marxist contradictions and dialectics. Rather, the general condition of life is that all complex phenomena contain operational chains that contradict each other.

Out of these daily uses of the terms tangle, entangle, and entanglement, there seem to be four key inflections of meaning that will also be seen to be present in scholarly debate about entanglement theories: (1) Entanglements involve a mass of strands. It is not enough to focus on a few variables at a time, or to make mono-causal arguments. Rather, it is necessary to explore the multiple threads and to pursue their heterogeneity. Entanglements are assemblages in which there are components and linkages of many types (material, social, economic, symbolic, etc.). (2) These different threads are often in contradiction with each other, as the example above indicates. (3) The threads are in such a mess of jumbled knots that it is difficult to sort them out as an analyst, and it is difficult to extricate oneself as a social actor. There is the idea of being

caught in a snare or trap. (4) As a result of the other three factors, problem solving is hampered or obstructed such that movement forward is channeled. There is path dependency.

The notion of entanglement has been used in a wide variety of scholarly debates. In biology there is often reference to the famous phrase at the end of *On the Origin of Species* where Darwin writes: "It is interesting to contemplate an entangled bank, clothed with many plants of many kinds, with birds singing on the bushes, with various insects flitting about." Many developments in biology focus on coevolution and symbiosis between humans, plants, and environments. Indeed, recently authors such as Evelyn Fox Keller have discussed a new Extended Evolutionary Synthesis in which culture and genes are not seen as separate forms of transmission but able to enter into each other through epigenetic and other processes. Culture and biology are thus thoroughly entangled. But perhaps the field in which entanglement has most influence today is in quantum theory in physics, where entanglement describes the mechanical phenomenon in which the quantum states of two or more objects have to be described with reference to each other, even though the individual objects may be spatially separated. This implies that the movement of an object cannot be predicted by reference to local conditions.

In philosophy, the work of Deleuze and Guattari has long been influential in moving away from hierarchical systems of classification and origination, and emphasizing the rhizomic links that flow between entities. Rather than searching for origins and hierarchies of causes, the focus is on the complex ways in which things are caught in webs. In anthropology and the cognitive sciences there has been a strong focus in recent decades on the ways in which perceptions and notions of self are distributed beyond the physical body. For example, Marilyn Strathern has talked of enchainment or distributed personhood. The term "enchainment" as used by Strathern refers to Polynesian and Melanesian cultures where persons are "dividuals" or "partible persons"—that is, persons are the products

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of chains of socially reproductive acts, so there is no division between the social and individual persona. Other approaches in anthropology have explored different ontologies. For example, Descola has described four different ways in which the relations between humans and animals are construed in different societies: animism, totemism, analogism, and naturalism.

Taking us closer to the notion of material entanglement are the many approaches that have described colonial encounters in terms of the ways in which communities get caught up in each other. In her work on contemporary South Africa, Sarah Nuttall describes the historical entanglements between blacks and whites. The more whites dispossessed blacks, the more whites depended on blacks (for labor) and the more blacks depended on whites. In their dependence on blacks, whites erected an ideology of separation and difference—racism. In effect, Nuttall describes a co-dependency. She problematizes simple oppositions between colonizer and colonized, metropole and colony, center and periphery, domination and resistance. She talks instead of an entanglement or “web, carrying with it the notion of interlacing, an intricacy of pattern or circumstance, a membrane that connects.” More influential for the work of archaeologists has been the work of Nick Thomas (1991) who writes of western and nonwestern peoples “mutually entangled in an array of rights and obligations, people who are ‘reciprocally dependent’” (Thomas 1991, 14) in the exchange of objects in the processes of colonialism. “The notion of entanglement aims to capture the dialectic of international inequalities and local appropriations” (Thomas 1991, 207). Rather than opposing European and indigenous, global and local, capitalist commodity and reciprocal gift, domination and resistance, Thomas’s work has influenced archaeologists studying colonial interactions (such as Dietler, Gosden, Jordan, Orser, Silliman, and Stein) in order to attain what Martindale describes as “a more historically accurate consideration of the complexities of the colonial encounter.”

While direct discussions of entanglement in archaeology are often influenced by the work of Nick Thomas on “entangled objects” there is a broader influence from studies of material agency and materiality. Since the 1980s, many

archaeologists have followed the work of Pierre Bourdieu on theories of practice and have argued that material culture can be actively employed in social strategies rather than being a passive behavioral response to adaptive conditions. The study of material culture (Miller 1987) and materiality (Meskell 2008) has had much impact on the ways in which archaeologists study humans as agents and things as agents, and there has been a lively debate on what the notion that things can be agents might mean. One of the outcomes of this discussion has been a critique of social theories in which humans are central, without things playing a major role. There has been discussion of a relational archaeology (e.g., Watts 2014) in which identity and causality are seen as dispersed, and there has been the claim for a symmetrical archaeology (Olsen et al. 2012) in which equivalent weight is given to humans and things.

The calls for a symmetrical archaeology have a more direct source of inspiration in the work of Bruno Latour. The study of socio-material networks by Latour has also had a very direct influence on material entanglement approaches in archaeology, although we will see below that the notions of network and entanglement are very different. Sociologists have tended to see the social world as about interpersonal relations. But Latour, Law, and Knorr-Cetina have come to see how engines, measuring instruments, laboratory probes, and detectors play a part as actors in structuring social relationships. These authors explore the production of scientific knowledge in the laboratory, but they also argue that similar social/thing processes occur more widely. They focus on the actor networks of big things like the French computerized rail transportation system called ARAMIS (Latour 1996), but they also look at small things like pipettes, paper blueprints, computer screens, and so on. The aim of this type of approach, often termed Actor Network Theory (ANT), is to focus on relationality rather than on apparent fixed and essential dualisms such as truth and falsehood, agency and structure, human and nonhuman, before and after, knowledge and power, context and content, materiality and sociality, activity and passivity. It is not that there are no such divisions but that the distinctions are effects or outcomes. As Law states, “They are not given in the order of things.” Thus, ANT

conducts a “semiotics of materiality.” It takes the semiotic focus on relationality and applies it to all materials, producing a relational materiality.

Other approaches focus more on flows and meshworks. For example, Tim Ingold (2010) places more emphasis on the ways in which humans and things co-construct each other in the practices of making. He explores how things are always changing in relation to humans and their perceptions. Environments are landscapes that are lived in and moved around, a pebble is different depending on whether it is wet or dry, a basket emerges out of the interactions between reeds and humans as it is made. Karen Barad has developed a theory of agential realism in which objects do not just exist and then interact. Rather they emerge through their “intra-actions.” Because everything is so entangled in everything else, when we observe something we have to make a “cut” that includes and excludes, so that the boundaries of entities are always temporary constructs. In reality, there is no interaction between separate entities, only actions within the whole, intra-actions.

A similar set of moves can be discerned in the archaeological accounts of material entanglement. Archaeologists have long studied the material properties of things, and the subfield of archaeometry has been devoted to chemical, physical, and biological techniques for understanding how material things were made and used and discarded. There has also been extended study of the operational sequences by which things are procured, manufactured, used, and thrown away. The main approaches have been of *chaînes opératoires* in the French tradition as described by Leroi-Gourhan and Lemonnier and behavioral chains in the American tradition as discussed by Schiffer. While these approaches have, in their different ways, been very effective at unpacking the ways in which material things can be studied, they have been less effective at developing a theoretical framework that links them to the social world. Things are largely seen as objects of human action rather than as co-constituting the social.

Material entanglement approaches in archaeology result from a critique of anthropocentric approaches but also from a critique of networks. For example, I have defined entanglement in terms of four types of dependency (Hodder

2012): how humans depend on things (HT), how things depend on other things (TT), and how things depend on humans (TH). If we add the obvious point that humans depend on humans (HH), then entanglement, at one level, is simply the addition of these four sets of dependences and dependencies.

$$\text{Entanglement} = (\text{HT}) + (\text{TT}) + (\text{TH}) + (\text{HH})$$

The defining aspect of entanglement with things is that humans get caught in a double bind, depending on things that depend on humans. Put another way, things as we want them have limited ability to reproduce themselves, so in our dependence on them we become entrapped in their dependence on us. Thing dependence on humans entraps humans into investment and care. But this is only because humans are so utterly dependent on things in the first place for all their physical and emotional and cognitive needs, and it is amplified because things depend on other things.

Within this definition, rather than simply identifying links in a network, attention is paid to the complex relations that comprise those links. In particular, a great load is placed on the term “depend.” There are various inflections of meanings in this word. On the one hand, dependence means reliance; it also has a contingent notion as when one says “it all depends.” On the other hand, dependence or dependency involve constraint, as when two people are in a co-dependent relationship that is mutually destructive, or as when colonial powers constrain the development of the colonized (see above). Thus, another way to define entanglement is to say that it is the dialectic relationship between dependence, often productive and enabling, and dependency, often constraining and limiting. Humans and things, humans and humans, things and things depend on each other, they rely on each other, produce each other. But that dependence is in continual tension with boundaries and constraints as things and humans reach various limits (of resources, of material and social possibility) that are overcome by, that demand, yet further dependence and investment. Entanglement can thus be defined as the dialectic of dependence and dependency between humans and things. Within the networks and flows there is a “caught-up-ness.”

However, it is difficult to hold fast to these initial definitions of entanglement as the sum of HT, TH, TT, and HH dependencies and their dialectical relations. Such a characterization appears to separate subject and object, culture and nature, in ways that have long been critiqued. Human being is always already dispersed and distributed into the world; there is no environment separate from human culture and society. It is thus difficult to talk of TT dependencies without human involvement, or of HH dependencies without things. Separating out TT, HH, TH, and HT dependencies from overall entanglements is difficult. A more satisfactory definition of entanglement accepts that entanglement is but a metaphor. It is a metaphor that tries to capture the contradictory messiness of the heterogeneous flows and counterflows that produce, enchain, and encompass entities (humans, animals, things, ideas, social institutions).

One technique that can be used to study entanglement is formal network analysis. “Tanglegrams” can be drawn that show all the dependences and dependencies between entities in a field of interest. This approach is very effective at exploring the multiplicity of links between entities and it is good at helping to define hubs and concentrations within the overall messiness of entanglements. It is less good at exploring the nature of the links between entities, the dependence and dependency, but other forms of quantification can be used here (Hodder and Mol 2015).

Another applied aspect of entanglement theory is the study of path dependency through time. Because the links between nodes in entanglements are so complex and heterogeneous, and because humans become invested in things, it becomes difficult to change paths. Changing one thing has so many effects on other things that there is constraint in moving forward. It becomes very difficult to move backwards and disentangle. A good example is provided by the work of Dorian Fuller (Fuller, Allaby, and Stevens 2010) who has shown how the genetic changes that produced domesticated plants resulted in the plants becoming dependent on humans for their propagation. There were advantages for humans in using domesticated plants: they provided more food per unit of land. But, on the other hand, humans became trapped in extra labor—the threshing and winnowing required in order to

release nutrients from domesticated grains. Once this step had been taken, it was difficult to go back. There are societies that move back and forth between farming and hunter-gathering, but in many parts of the world the dependence on domestic crops led to numerous other changes such as larger settlements, more complex social systems, larger ritual monuments, and greater trade. Once all this had been entered into it was difficult to return to a hunter-gatherer way of life; humans had entered a pathway that was difficult to reverse.

Another example is provided by the adoption of pottery in the Neolithic of the Middle East. In the initial stages of pottery use at the site of Çatalhöyük, the main use was for food serving. Through time, the affordances of pottery became realized and the entanglements of pottery increased to include cooking and then storage and social display. In the initial stages of this process it would have been relatively easy to stop the dependence on pottery, but as the entanglements increased, “points of no return” were reached so that it was difficult to give up and disentangle from pottery.

In conclusion, it is often said that the study of material entanglement has a negative hue, imparting a sense of being trapped in pathways that lead in specific directions. Part of the attraction of the term may be that it resonates with a wider global sense of being trapped. Increasingly we seem met by intractable problems such as global warming, or the gridlock of international agencies such as the United Nations that seem powerless to act, or by the inability to introduce gun laws in the United States despite repeated mass shootings. In terms of food consumption, we are trapped in the nonsense of throwing away large amounts of the food that is produced; and campaigners such as Alice Waters argue that we are imprisoned in fast food, leading to obesity and a high incidence of diabetes. In small and large ways, we seem increasingly stuck. These everyday senses of being cornered and unable to find a way out are perhaps what provide entanglement its traction in the contemporary world.

On the other hand, it is important to stress that archaeological studies of material entanglement also allow exploration of how a particular present and a particular notion of human and of thing have been produced. The approach is

fundamentally historical and particular, and it demands exhaustive analysis of the complexity of human–thing relations in all their specificity. It allows archaeologists to explore how humans entered down pathways that produced global warming and other contemporary predicaments. It allows us to understand the full complexity of the problems in cases where entrapments were entered into millennia ago. But it also encourages us to ask whether there are fundamental alternatives. After all, if humans are only humans within their entanglements with things, then it must be possible to conceive of other forms of dependence in other worlds of things. It must be possible to “be human” and to “be a thing” in other ways.

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Material Metaphor

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In linguistics and literary studies, metaphor is widely understood as the application of a name or descriptive term to an object, person, being or situation to which it is not literally applicable. As such it is a communicative trope, and its purpose is to invite novel appreciation of a quality or qualities that are familiar from the source object to the subject object concerned. The key differentiating characteristic of metaphor, which distinguishes it from simple substitution such as occurs in metonymy (wherein the name of something is used in place of naming the thing itself: as in the use of “the crown” for “monarch”), is that it involves *transformative* comparison. So although a metaphor may at root be metonymical, in its deployment in discourse it travels further. As such, it intensifies the effect of such comparison not only by reproducing accepted meanings, but also by creating novel ones.

Anthropologists have identified metaphor as permeating the cultural representation of social experience and as being used actively in the structuring of discourse, for instance via the use of animal categories as a key source of analogy. Such classification is not, however, the result simply of cognitive norms or ordering devices. Rather, it is motivated: metaphor is central to social strategies involving the construction and sustaining of individual and group identities, inclusion/exclusion, and so on. In particular, ritual activity has long been identified by anthropologists as a key locus for “social metaphor” deployed strategically. For example, the Fang cult of *Bwiti* has been seen to exemplify two crucial aspects of such metaphorical usage. One is that metaphor not only expresses “cognitive mapping”, but also structures it. The second is that this structuring is achieved by drawing upon the parallel capacity of both metaphor and ritual to produce dramatic shifts in understanding. So,

for instance, ritual events can employ linguistic metaphors of transformation while the ritual process itself is metaphorically transformative.

Meanwhile, there has been much debate in English, as in other languages, as to whether all human thought and language is in fact metaphorical. It is possible, according to George Lakoff (1993) and others, to regard metaphors as models for understanding the world, and therefore as fundamental to cognition. The danger that has been noted about such an all-embracing understanding of what metaphor comprises is that it may bring into doubt whether any distinction is possible between literal and metaphorical statements. However, whatever are the broader metaphysical implications of linguistic or literary expressions involving transformative comparison, it is the use of metaphor primarily as a device deployed strategically in social discourse that has the greatest potential for identifying and exploring the way in which social relations and social structures are sustained and reproduced in dialogues within and between the verbal, literary, and material domains.

There has not been a long history of the discussion of the relevance of metaphor, and metaphor theory, to archaeology. The first published use of the term “material metaphor” appeared in 1987 (Ray 1987, 67; cf Preucel 2006, 142–143), but while the relevance of metaphor to archaeological inquiry has been noted both implicitly and explicitly in a number of archaeological writings (see below), there has been little extended treatment since then. In the only book-length discussion of metaphor and material culture published so far, Christopher Tilley (1999) identified many examples from cultural anthropology and ethnography of how, in pre-industrial societies, the natural world, animals, and the inherited environment provide a rich source of metaphors that is referenced materially and expressed durably through the creation and deployment of artifacts expressive of the relations concerned. It is thus the “coded” visibility of specifically *material* metaphor (Tilley used the somewhat misleading term “solid metaphor” interchangeably) that

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makes it such an effective communicative device. Tilley referred to one particularly vivid example of this process in action from John Layard's 1930s researches among the peoples of northern Malekula in Vanuatu. Here, four categories of boar were recognized according to the stages of growth of their tusks. These categories were mapped against the passage of time through the lives of the men who had raised the boars, and their sacrifice was implicated in the rich field of symbolism and metaphor that linked the biographies and reproductive lives of both men and women (Tilley 1999, 53–54).

Meanwhile, in other Pacific Ocean contexts, canoes have been noted by field researchers as implicated in social relations and discourse in reference to the human body, and especially to orifices and openings, and states of being. Elsewhere in the world, these bodily references have been carried over into other aspects of technology, such as ironworking, and into descriptions and uses of portable items such as baskets and axes. Working back the other way, archaeologists focusing upon ancient contexts have sought to interpret patterning in, for example, the treatment of corpses and what was included in burial assemblages (cf Bruck, 2004, in reference to Early Bronze Age funerary contexts in southern Britain), or in the orientation of the doorways of circular huts, as evidence for the metaphorical evocation of social relations or body parts (or both). The impact of the transformative nature (via kilns and furnaces) of both pottery manufacture and metal-working in Bronze Age Europe has, meanwhile, been explored in terms of its metaphorical associations (Barber 2003, 165–170).

The efficacy of metaphors, whether material or verbal or literary, is greatest where a transposition of form draws sudden and unusual attention to a transformed condition, or relationship. In verbal discourse, this is achieved through placing two entities not simply into contrastive, but into actively incongruous, relationship to one another. In nonverbal discourse, the creation of an object in a familiar form but in another material—that is, in the practice of *skeuomorphism*—most graphically draws attention to the compared entities, and potentially carries the association of the “source” form into new contexts. Where this transformation and translation has involved the creation of a more durable version of an object in an otherwise

perishable form, it enables archaeologists to learn about the form of the “source” item irrespective of whether the organic artifact has survived, for instance in waterlogged deposits. While this can provide a more complete picture of the past material culture of the relevant society, it is not the sole interest archaeologically. This is because the question of the motivation to have made and deployed the *skeuomorphic* item in the first place is at least equally important. So, if for example the labor and economic power of women in marketing is habitually referenced by their making and using baskets, the *skeuomorphic* transposition of baskets into pots may render this economic role both more visible and more durable. The creation and deployment of *skeuomorphs* of a range of objects including baskets, calabashes, wooden stools, and title-staffs at tenth-century CE Igbo Ukwu in southeastern Nigeria was in this way highlighted in order to suggest that a series of abstract concepts and excluded persons and actions was brought into presence in a context (the ritual store-house of a senior male lineage group) where some or all of these practices and persons may “normally” have been excluded (Ray 1987).

Tamara Bray (2008) has meanwhile noted how Inca elites created a specific set of fine and highly figurative ceramic vessels which through their decoration metaphorically referenced clothing that was prescribed for use by the social group concerned. It proved possible to explore the depth and breadth of allusion involved in this decoration in reference to ethnohistoric evidence for the ordering of Inca society. A metaphor of “containment” was expressed through painted images of particular kinds of cloth on the sides of highly elaborated pots. These cloths were those used as clothing wrappers by the elite members and so the pots served as the (literal) embodiment of the prescriptive codes of practice and aesthetics concerned. Such prominent symbolization in effect appropriated the domain of the domestic to the elite and naturalized the social stratification that maintained the structures of dominance and subordination that had developed in the Bolivian Andes.

If the motivation for the creation of complex “material metaphors” can in many cases be seen to have been strategic or negotiated, it is also important to assess why a particular density of such co-referencing may have taken

place at a particular place and time. So while at tenth-century Igbo Ukwu a key motivation to such density of allusion was surely to reference the power of whomsoever had commissioned or “consumed” such materials, other reasons for the extravagant use of resources to create the extensive assemblage of elaborate metalwork (in particular) were detected. One such purpose was to mark a key historical juncture at which a series of abstract concepts, associations, and social relations (especially and specifically around power) were made “concrete,” both conceptually and materially. This juncture was connected with the amassing of wealth through trade, exemplified by the presence of ivory elephant tusks and of masses of exotic beads. Some particular associations were understood as constituting “historical metaphor.” In the first place, a “foundation myth” for the origin of agriculture and the development of a sacralized leadership system locally was cited in the representation in bronze of an oral tradition concerning an act of sacrifice of the “first” male and female offspring of the mythic lineage founder. This act was said to have brought food to the Igbo: and the enactment of skin scarification symbolically recreating the farming furrows denoted membership of the privileged foundational lineages. The second was through the “choreography” of a particularly richly furnished grave of one of the ritual leaders themselves, which referenced the ceremonies of both symbolic and actual death and rebirth associated with the holding of a particular lifetime-only leadership role. The manner of placing of the body in an upright position, supported by staffs, and sat on a stool that denoted the office concerned was complemented by the inclusion of a range of items, each of which contributed metaphorical references of their own.

An entirely contrasting question surrounding “material metaphor” arises from the interpretive practices of archaeologists themselves. Tilley usefully pointed out (1999, 82–101) how the metaphorical use of the term “megalith” in European prehistory served as a kind of short-hand that nonetheless entrapped the users into a self-sustaining, and also limiting, discourse. Archaeologists have deployed particular conceptual metaphors more self-consciously, however, to tie together a series of ideas about historical processes. Prominent among such theorizing was

a study by Ian Hodder in 1990 that dwelt upon the “Neolithic revolution” in western Asia and Europe, in which “domestication” was viewed as encapsulating as much a metaphorical relationship between humans and other species as an ecological or materially economic one. In that study it was the development of an opposition between the “domus” (as house and home) and the “agrios” (the world as perceived as being external to that of human society) that was seen as a prerequisite of the control over the reproduction of plants and animals that occurred in the relevant centuries. As such, it was proposed that the process of “becoming Neolithic” was one that involved the “domestication of society” itself.

The question inevitably arises from the breadth of studies involved, as to whether there can be a *general* theory of metaphor in archaeology and material culture studies. Tilley (1999, 260ff) certainly thought so, and argued that “solid” metaphors are not substitutes for linguistic metaphors or translations of them into material form (Tilley 1999, 263). Instead, the relationship between material metaphors and verbal/literary ones is interdependent or dialogical. So while verbal metaphoric expression often makes reference to, and carries most force using, imagery based in the material domain (“Peter was the rock upon which our Church was built,” for example), a material object may make metaphoric reference to a relationship normally articulated in words. Others, meanwhile, have seen certain material metaphors as having had a key role in the formation of emergent ontologies and as being in this way central to a “cognitive” reordering of social experience. Gary Webster (2001), for example, interpreted the form of late Nuragic period pots in Sardinia as representing a tension between an idealized represented “historical” set of social relations and those that actually obtained in a period of marked change.

Moreover, archaeologists have seen metaphorical structures as key means by which human cognitive development itself occurred in the past. Fiona Coward and Clive Gamble (2010), for example, have suggested that the corporeality of material culture and its potential as a source for both mnemonic and metaphor was drawn upon in periods even antecedent to the development of sophisticated linguistic expression. They cite the way in which the

production of flint/stone blades from cores produced a technology that vastly expanded the field of material expression; and how the disarticulation and re-articulation of animal bones facilitated the citation of human–animal relations from deepest prehistory.

Metaphor has in this and in other ways therefore become drawn into contemporary theories of materiality in archaeology, and in particular into conceptualization of the motivation and consequences for human engagements with things, and the relational nature of such engagement. One manifestation of this has been developed in reference to another early Neolithic site, Catal Huyuk in central Anatolia in modern-day Turkey. This has involved an exploration of the relevance of material metaphor to the concept of “entanglement” (Hodder 2012). According to this conceptualization, people not only habitually make links across domains both material and nonmaterial, but also become entrapped within their complexities. Metaphor plays a role in helping people find paths through the ideational maze that ensues, to bring “intellectual coherence” to their entanglements (Hodder 2012, 123).

The importance of metaphor, as Coward and Gamble have emphasized, is that people habitually think and act relationally, that is, in reference to the presence, actions, and motivations of those around them, and to the inherited and dynamic environments they inhabit. Metaphor facilitates contrast and comparison. It is a tool for thinking about the relationship of one phenomenon to another, one situation, condition, or state of being or behavior to another, and one person to another in terms of their practical and interactive “projects.” Material metaphors are durable and can serve as mnemonics of past states, past people, and what might be termed “absent presences.” Gavin Lucas (2012) has made an important point here in reference to archaeological residues and their intrinsically referential nature. The “archaeological record” is not a text, because it has rarely been composed deliberately in order to act communicatively, for the purposes of “reading;” many, perhaps most, residues reflect the unintended consequences and outcomes of action. Nonetheless, absent presences are routinely implicated in archaeological residues. The “equipment” concerned is also made up of practice and knowledge that people need to equip

themselves with in order to perform almost any action involving others. In this way, metaphor, as a practical resource with its rhetorical and cognitive attributes, but above all its relational and discursive power, stands at the core of social being rather than marking its periphery.

SEE ALSO: Embodiment; Interpretation; Material Agency; Material Culture; Material Entanglement

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Material Symbols

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Material symbols can be defined as symbols that have physical form. They consist of artifacts, art objects, buildings, monuments, landscapes, plants, animals, and even people. They thus possess an existence and durability that transcend the evanescence of the spoken word. Their physical character gives material symbols a permanence that can help establish and fix social meanings. As Hannah Arendt (1958, 137) put it, “the things of the world have the function of stabilizing human life and their objectivity lies in the fact that men, their ever-changing nature notwithstanding, can retrieve their identity by being related to the enduring sameness of objects.” Throughout this entry, I will use the term material symbols to refer to material culture, things, objects, and artifacts more or less interchangeably.

Because material symbols are a kind of sign, it is helpful to begin with a discussion of signs and how they carry meaning, the subject of the field of semiotics. Signs are generally defined as words or things that stand for something in the mind of someone. This “standing for” relationship is quite complicated and has been the subject of considerable research in philosophy, semiotics, linguistics, cognitive science, anthropology, and archaeology. Some scholars regard all signs to be arbitrary in the sense that the relationship between the sign and the thing being referred to is determined only by cultural convention. Other scholars regard some signs to be motivated in the sense of having a nonarbitrary relationship with their referents. All scholars agree that signs only obtain their meaning in context. Signs must be perceived as such by someone at a particular moment in time and different actors may regard the same sign differently. This variation is the basis for the claim that culture is a symbolic system

and highlights the fact that all interpretation is intersubjective.

Historically speaking, there are two main approaches to the study of signs. The first is the approach developed by Ferdinand de Saussure. Saussure conceived of semiology as a new science related to social psychology and devoted to the investigation of the general principles of signs. He regarded it as a unified field that was based upon language and including writing, sign language, Braille, symbolic rites, honorific speech, and military signals. Saussure recognized that his new science could be applied to all of culture, and famously asserted that by studying rites, customs, and so on as signs, it would be possible to create a semiological science complete with its own natural laws.

This insight was taken up and further developed by Lévi-Strauss and Barthes as part of their structuralist programs. Lévi-Strauss regarded linguistic phenomenon as a self-contained, structured whole and the appropriate model for the study of material culture. He applied his approach to the study of kinship, mythology, totemism, and history. Barthes advocated Saussure’s structural linguistics, but broke with Saussure on the generality of semiotics. He regarded it to be a subset of linguistics due to the primacy of discourse. He broadened out its subject to include literary texts, art, music, and fashion. These studies were widely influential and contributed to the emergence of semiotics as a major movement in literature and cultural studies in the 1970s and 1980s.

The second approach is that advocated by Charles Sanders Peirce. Peirce conceived of semiotics as an irreducible form of life encompassing man and nature and indeed the entire universe. Signs not only exist in the world, they also grow and continually produce other signs. All cognition then is a semiotic process that is mediated by signs. Peirce’s view of semiotics is inextricably linked to his view of pragmatism. To understand the meaning of a concept, one needs to examine its various contexts of use. However, this, by itself, is insufficient. Meaning can only properly be understood with reference

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to those logical concepts that establish a belief and that, in turn, facilitate the belief becoming a habit of thought. In use and experience, the sign's meaning grows.

Peirce defined the sign/referent relationship as being composed of three sign types: icons, indices, and symbols. *Icons* are signs that refer to an object on the basis of resemblance. They are "mimetic," an example being a diagram or a painting. An *index* is a sign that denotes its object by being affected or modified by that object. A weathervane, for example, points to the direction of the wind based upon the action of the wind on the tail of the weathervane. A *symbol* is a sign that obtains its character by virtue of some law, usually an association of general ideas. In this case, meaning is the result of convention. For example, a flag has no inherent meaning, yet it is commonly taken as a symbol of a nation. These three sign types have a hierarchical relationship such that symbols imply indices that themselves imply icons.

Archaeologists drew liberally from linguistic perspectives in the development of symbolic and structural archaeology. In a classic essay, Hodder (1982) reviewed the limitations of functionalism and structuralism, and highlighted the importance of the symbolic association of things. He argued that the meaning of an object resides not only in contrast to other objects, but also from its associations and uses in a network of references and implications. He further held that material symbolization is not a passive process and objects and activities "actively represent and act back on society" (Hodder 1982, 10). Reference is thus both dynamic and social.

Hodder (1990) demonstrated the value of this insight in an influential case study focusing on the European Neolithic. His main thesis was that symbolism must be addressed in order to understand adequately social and economic change. He proposed that in Europe and the Near East a particular set of concepts was central to the origins of agriculture and a settled mode of life. These concepts relate to the house and home—"domus"—and they provided a metaphor and a mechanism for social and economic transformation. As the wild was domesticated through ideas and practices surrounding the domus, people were brought in and incorporated into the social and economic life of the village. Over the

following millennia, cultural practices relating to the domus continued to change and develop, until finally they were replaced by a new set of concepts based on the warrior, the hunter, and the wild.

Shanks and Tilley (1987, 130) extended Hodder's symbolic approach in their consideration of material culture as an objectification of social being. They proposed that material culture does not directly reflect practices and structures, but rather mediates them through its own formal logic. Shanks and Tilley (1987, 131) identified three social fields in which material culture operates: technological, communicative, and ideological. Material culture can facilitate technological interventions as humans engage with the natural and social world. It can provide a communicative medium of symbolic significance. Finally, it can provide a medium for social domination as an expression of power and ideology. Significantly, they observed that material culture may operate in all three fields simultaneously.

Inspired by the post-structural critiques and discourse analysis, Tilley (1999) introduced the idea that material culture can be understood as a "solid metaphor." He noted that solid metaphors are not substitutes for linguistic metaphors, nor are they translations of them into material form (Tilley 1999, 263). Rather, they condense meanings in a manner that might require a number of linguistic metaphors to accomplish a similar effect. Material metaphors typically signify in nonarbitrary ways linked to their specific qualities, such as shape, structure, color, texture, and form. Tilley identified the human body as a rich source of metaphors for organizing and understanding the social world. As he puts it, the human body is "metaphorically intertwined with the social body and itself patterned and constructed through this integration" (Tilley 1999, 37). He observed that if the body is society, then parts of the body may represent different parts of society. He drew attention to the common right and left dualisms where oppositions are set up between sacred and profane, birth and death, light and dark, and so on. He noted that spatial oppositions such as inside and outside, near and far, center and periphery are based upon the body.

Tilley applied his approach to the study of southern Scandinavian rock art dating to the end of the Bronze Age. In a detailed analysis

of Högsby, Sweden, he concluded that there is a structural order to the rock art in a south to north sequence. He interpreted the rock art as providing a focus for processions and ritual ceremonies associated with becoming human. He regarded the rock art narrative at Högsby as linked to the regeneration of life, the passage of the seasons, and the relations between land and water. He regarded specific images as having multiple meanings, “multidimensional chains with shifting and transformational relationships between signifiers whose meaning becomes contextually transformed according to their location in the series of carved rocks and their relationships to other signifiers on individual carving surfaces” (Tilley 1999, 173).

The language model has proven to be of limited value for material culture. Hodder (1982) observed that, unlike spoken language, material culture meanings function in nondiscursive and implicit ways. Moreover, material symbols are not arbitrary, as are words, since the content of the sign affects the structure of its use. Shanks and Tilley have also critiqued the linguistic model. For them, material culture is a coded sign system that constitutes “its own material language” in the context of production and consumption (Shanks and Tilley 1987, 101). It does not simply reflect the signification structures of language in another form. Rather, it is “constituted in terms of a spiraling matrix of associative and syntagmatic relations involving parallelism, opposition, linearity, equivalence and inversion between its elements” (Shanks and Tilley 1987, 103). Material culture is thus implicated in a material discourse that is bound up with social practices involving power, sectarian interests, and ideology.

Some archaeologists have turned to the semiotics of Peirce as a means of addressing the limitations of a Saussurian model. Preucel (2006) has reviewed the advantages of a Peircian perspective. For example, Saussure’s dyadic sign theory brackets off things-in-the-world because of its emphasis on the language system. Peirce, in contrast, has a place for things in his tripartite sign formulation. Saussure emphasizes unmotivated relations and regards the signified–signifier relation as arbitrary. It implies only the oppositional relation of difference. Peirce recognizes arbitrary relations with his symbols, but he also identifies two kinds of motivated relations, namely icons

and indices. Saussure focuses on the structure of representation. Peirce focuses on the pragmatics of mediation and how signs generate new signs through situated social practices.

Some scholars have investigated how different kinds of signs were bundled in strategic social practices. Preucel (2006) investigated the linguistic and material elements of indigenous discourse during the period following the Pueblo Revolt of 1680. Historical documents reveal speech acts by Pueblo Indian leaders seeking to persuade their followers to relinquish Spanish customs and practices and return to a lifeway consistent with the laws of their ancestors. Preucel then examined settlement location, architectural form, and pottery design and found archaizing elements. He concluded that these material symbols functioned alongside linguistic discourse as mutually supporting practices and that they collectively mediated a new form of temporality and created a new social being.

Joyce (2007) examines the recursive, experiential aspects of figurine use in northern Honduras between 1,100 and 200 BCE. She notes that her study is, properly speaking, a study of meaning-making rather than meaning *per se*. She observes that the figurines themselves point toward the existence of active social agents making marks that we recognize as meaningful. She finds that different hair treatment functions as a special locus of iconic significance, and finds that hair-styles appear to vary with the age of the represented person. She then notes that the symbolic meaning of these figurines remains elusive because of the difficulties associated with understanding conventions associated with their community of production and use. Her analysis thus reveals the limits of interpretation, and multiple ways in which signs can be understood by both contemporary scholars and past actors.

There is a growing interest in studies of networks and entanglements. Knappett (2011) has drawn attention to the importance of network thinking combined with the advantages of shifting focus from material culture to materiality and from objects to assemblages. Inspired by Bruno Latour’s actor network theory, he emphasizes the need to decenter human agency and consider an “enactive” approach where humans and nonhumans bring each other into existence. Each enables the other, thereby locating agency

jointly in them. In a similar fashion, Hodder (2012) argues that people and things have a long evolutionary history. Their entanglement can be seen as emerging from the dialectic of dependence (reliance) and dependency (constraint and limitation). Entanglement is both a condition of being in the world and a process of entities linking together in networks or assemblages. Significantly, entanglements have temporalities that things impose on humans due to their natural lives and this gives entanglements a direction.

Another important research trajectory has been the origins of symbolism and modern behavior. This topic is usually linked to language and tool use. Some scholars hold that symbolism developed in Africa, in conjunction with the gradual biological evolution of our species. Modern behavior is linked to the emergence of modern language on the assumption that enhanced communication ability would have had clear evolutionary advantages. Yet other scholars believe that symbolism and cultural modernity may have developed independently or been acquired at different times, by a range of hominids, including Neandertals. Most scholars agree that a fundamental turning point in human evolution was when humans were first able to use material symbols to locate memory outside the body. The abstract patterns engraved on pieces of ochre found at Blombos Cave in South Africa and dating to 100,000 years ago appear to be among the earliest manifestations of this ability. Donald (1991) proposes that “external symbolic storage” constitutes a major factor in human conceptual development. Similarly, Mithen (1996) argues that the conscious use of material culture to store information is a fundamental feature of any specialized (domain-specific) intelligence. This is a dynamic subfield and it is likely that additional refinements and new theories will emerge with additional discoveries.

Cognitive archaeology has emerged as a subfield focusing on the cognitive processes related to the changing conditions in the material domains of life. Significantly, Renfrew defines the field as the study of the special human ability to construct and use symbols. His “material engagement theory” advocates shifting attention away from objects to the fluid and relational transactions or relations between people and things (Renfrew

2004). Malafouris (2013) has further developed Renfrew’s approach. He provides empirical and historical evidence for the ways in which material artifacts are not merely aids to an internal cognitive process, but are in fact integral to the process itself. He also introduces the idea of enactive signification. Enactive signification refers to the mode of signification wherein the meaning of a sign is not symbolically encoded in the sign as a representation, but rather is located in the interactive process itself. For example, he suggests that numeracy was not merely encoded onto clay material as though it were a recording of a mental process, but rather, the clay itself acts as a means of providing signification by enabling a qualitatively different cognitive process.

Finally, it should be noted that several new studies, influenced by the “new materialisms,” emphasize the vital force of material culture in the world. The basic claim is that material culture needs to be radically reappraised and people and things need to be considered as ontologically equivalent. Archaeologists differ on the nature of this reappraisal. For some, this involves a shift from material symbols to vibrant materials. Jones and Alberti (2013, 23) argue that it is critically important to examine how materials and persons are assembled. For others, it involves the consideration of object agency independent of humans. This view underpins symmetrical archaeology (Olsen 2010) and various post-humanist approaches. These critiques are valuable in drawing attention to the boundaries of the materiality concept. However, they risk relegating real-world, social issues to secondary significance.

Material symbols are the primary physical expression of human sociality. They constitute the social resources for communication and the mediation of social practices. There continues to be considerable debate among archaeologists regarding how best to model material symbols in the communicative process. Do they function like language, or do they occupy their own separate domain? What does the decentering human agency mean for understanding material culture and the evolution of symbolic behavior? However these questions are resolved, it must be acknowledged that material culture and language are deeply imbricated, as a sociosemiotic

approach would argue. Linguistic acts typically accompany the use of things in context. Their fates are necessarily intertwined.

SEE ALSO: Material Agency; Material Culture; Material Entanglement; Material Metaphor; Mind and Cognition

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Memory and Remembrance

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Memory has been an intensively studied and theorized area within archaeology since the beginning of this century. Out of this debate has come a variety of perspectives, drawing on a wide range of research in the natural and social sciences. These have, in turn, led to a range of different definitions of what we mean when we talk about memory and how we might usefully research memory in archaeology.

It is helpful to begin by offering some definitions. The archaeological study of memory has been concerned with the material manifestations of memory and remembrance. Theory around memory and remembrance in archaeology has also been predominantly concerned with the operation and creation of memories at a group or social level. Additionally, recent theory around memory has drawn on a wider concern within the social sciences on embodied (see EMBODIMENT) and experiential understandings of the self. These can be contrasted with another, equally valid, set of archaeological questions around memory.

How do the results of current archaeological research contribute to the construction of memory (see MEMORY) in the present? In this entry, the aim is to discuss embodied theories of practice around memory. How did people in the past remember with material culture?

Classical philosophy on memory, from Plato's dialogues up to John Locke's concern with the "self," can be characterized as being concerned with an inward-looking analysis of personal and individual memory. By contrast, phenomenological approaches to memory in the work of Edmund Husserl and Maurice Halbwachs made an explicit link between the creation of memory and the experience of living within a group of people. Borić (2010) provides a detailed exegesis of this distinction from an archaeological

perspective, based on the work of Paul Ricoeur. This communalization of memory has been an important influence in the way that social theory has discussed memory as an explicitly social phenomenon, a property of the group rather than of the individual.

From both phenomenological traditions of philosophy and studies in cognitive science we can discern the importance of habitual, physical encounters in creating memory. Andrew Jones (2007) draws on Andy Clark's work in cognitive science to describe the interaction between the brain, the human body, and the world as one of overlapping "fields of interaction." The mind and, by extension, memory is created in the embodied interaction between the material world, the body, and the brain. This kind of habitual memory is often unconscious and it can be regarded as the foundation for people's integration in their particular society—their habitus in Pierre Bourdieu's terms.

Therefore, in contrast to "classical" philosophical and psychological examinations of memory, which treat memory as an internal property of individual identity, modern social theory has discussed memory, by definition, as a social phenomenon. The subset of this social theory which is concerned with embodied and material perspectives on memory is, for obvious reasons, the most relevant for archaeological enquiries into memory and remembrance. The foundations of the embodied social approach to memory were laid in Connerton's (1989) book *How Societies Remember*. In this work, Connerton treated memory as a cultural phenomenon and attempted to explore the ways in which group memories were transmitted in nonwritten ways. He showed the importance of ritual performances to inscribe social memory on the bodies of the participants. Connerton's work is also important for the connections it draws between the semi-unconscious habitual memory discussed above and other kinds of memory. For Connerton, habit-memory is one of three broad classes of memory claim, the other two of which are personal and cognitive memory claims. Personal memories "take as their object one's life

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history.” Cognitive memory claims are memories of abstract knowledge, while habit-memory is the memory of how to perform an action physically. These last two kinds of memory claim share the characteristic that you do not need to remember when you learnt something to make use of it (Connerton 1989, 22).

At this point it is necessary to consider in rather more detail the way in which the passage of time is experienced by people to create different kinds of memory. In *The Perception of the Environment*, Tim Ingold (2000) develops both a “dwelling perspective” and the concept of “temporality” to address precisely this issue: For Ingold, agency is developed through the experience of time and of memory.

People dwell within environments made by previous human activity. Everything they do is structured by those pre-existing environments and in turn their actions create new kinds of environment. Ingold develops this theme of temporality by coining the neologism “taskscape.” The “taskscape” can be thought of as an array of temporally related activities which is analogous to “landscape” as an array of spatially related features. Ingold (2000, 199) uses the phrase temporality (see TIME AND TEMPORALITY) to describe a conception of time, based on the phenomenological philosophy of Maurice Merleau-Ponty, and which is therefore not dependent on particular models of human consciousness and which does not need to be calibrated to a scientific measurement of time. For Ingold, people make time pass when they do things: Temporality is the time of the participant.

One useful contribution to thinking around the role of material culture in the transmission of memory is provided by the concept of the “index” used by Alfred Gell (1998) in *Art and Agency*. For Gell, the artist and the artwork are inseparably linked in time; in Ingold’s terms, the artwork is part of the taskscape of the artist. In addition, all artworks reference earlier works. They would not be comprehensible as art without this connection and through this link they connect the artist and the viewer to those earlier artworks. As they are making the artwork the artist is physically incorporating their bodily actions into the object. Gell (1998, 236–237) does not claim that objects themselves experience memory, or even that they work as an external store for human memories.

Instead he borrows the term “abduction” from semiotics to describe the way they permit people to make “causal inferences” about things that happened in the past. From the embodied perspective described above, we can see physical changes to artifacts and landscapes as evidence for the creation of memory in the past. This can potentially provide archaeologists with a methodology to investigate memory claims of all three types identified by Connerton.

Andrew Jones (2007) has analyzed the role of material culture in memory by drawing on the actor network theory (see ACTION THEORY) of Bruno Latour and colleagues. His focus is on the act of remembering, which he would see as both an embodied and social process; people require both other people and things in order to remember. Jones takes from Latour the insight that we do not need to give priority to either brains, bodies, or artifacts in this process. He refers instead to the act of remembering arising from the relationships between a “company of actors.” Therefore, for Jones, it makes little sense to make distinctions between internally or externally stored memories, or even between social and individual memories. Rather we need to think about material culture (see MATERIAL CULTURE) (broadly defined) and the way it acts to permit the practice of remembering. Objects can act as metaphors which crystalize and index short-term events. Monuments can index events which have taken place. However, they also have the properties of permitting or blocking certain kinds of physical activity. This is particularly important when it comes to the role of large-scale commemorative ceremonies, social remembering practices which are aimed at creating a particular kind of memory.

In his review of the role of memory studies in archaeology, Dušan Borić (2010) follows Jones in arguing that distinctions between different kinds of memory claim, while analytically useful within philosophy, are less helpful in archaeology. He proposes that archaeological analysis is better served by a temporal focus on the processes of memory, for which he draws on Ingold’s (2000) dwelling perspective. The first of these is the trace, the physical imprint of past actions. Borić points to the problematic status of the “trace” as something that has been treated as both a conceptual tool and a metaphor. However, for the purposes of this argument, “trace” can be thought

of as the embodied, materialized evidence of past actions, directly equivalent to Gell's (1998) "index." For Borić, "trace" leads to "citation." When people respond to traces they do so within a new temporal framework. So, rather than inferring past agency from indices, in the way suggested by Gell, Borić argues that people "cite" these traces in a new contemporary set of relationships. Remembering is a process that takes place in the present, drawing on the presently available "company of actors." However, the same traces and citations can be drawn upon in more than one present, which leads Borić to the third of his analytical categories, "recapitulation." By repeating practices in the same places, traces can be cited in ways that are both traditional and innovative. Therefore, material culture and landscape can be deployed to create and modify memories as well as to "preserve" them.

The importance of bodily performance is clear in all these accounts of the practice of remembrance. Formal bodily performance was also an important part of Connerton's analysis of the creation and managing of collective social memory, in his case focused on the large-scale rituals of organized religion and nation-states. Peterson (2013) has reviewed the specific importance of embodied performance at all scales of analysis. Following Jones in focusing on practices of remembering, it can be argued that even small-scale habit-memories require an embodied performance. Bodily skills, for example learning to work stone, are learnt from a combination of feedback from the material being worked with approbation from an experienced audience. What is being created in this case are indexing traces on the landscape, the artifact, and the body, all of which will be drawn on in future citations. As well as the stone tool and the production site, the lithic worker has created the kind of body that knows how to work stone. The citation and repetition involved in these performances is another instance of the continuity of practices of remembering across the scales from personal habit memory to large-scale commemorative performance.

Therefore, building on the literature discussed above, the archaeological study of memory and remembrance is characterized by the analysis of a number of important topics. These include: the relationships between people, landscape, and

material culture; evidence for embodied performances; transformations to bodies, objects, and places which act as indices or traces; and the ways in which these changes are cited and recapitulated in subsequent times.

A specific example of these processes being used to deliberately create lasting memories can be seen in Howard Williams' (2001) application of the archaeology of memory to the study of early medieval funerary rites at Sutton Hoo in Suffolk, UK. This site is a royal barrow cemetery dating to the sixth and seventh centuries CE which, alongside the famous ship burial, contains other high-status inhumation and cremation burials beneath 19 large barrows. The site itself is on a prominent location above the Debden estuary, which is likely to have lain on the contemporary route to the East Anglian royal site at Rendlesham. Williams argues that funerary performances at Sutton Hoo would have replicated the route from the sea to the cemetery taken by the ship in mound 1 before burial. Funerary processions therefore would be both citing earlier processions and making the dead visible by creating traces or indices to commemorate them in the landscape.

The most obvious of these traces would be the barrows that cover the graves. Williams analyzes the way that these barrows are structured by the indices of earlier activity and how they recapitulate and cite each other. He argues that the large complex barrows, which contain complex assemblages of material culture and evidence for animal sacrifice, are the physical traces of large funerals. They are widely spaced, which Williams argues is the result of each barrow being carefully sited in relation to existing monuments. This is interpreted as a way of deliberately creating physical indices of the dynastic connections between the different occupants of the barrows. Although there are no prehistoric barrows at Sutton Hoo, Williams cites other early medieval burials which cluster around pre-existing Bronze Age monuments, to suggest that the overall form of the pagan Saxon barrow is itself a citation of the deep past.

Williams analyzes the transformations around the inhumation burial in mound 17 to show how the ritual performance both cites earlier funerals and allows the incorporation of unique elements for that particular individual. Funerary

performance would have focused around the deep oval pit at what would become the center of the mound. A complex assemblage of grave goods was used to create a particular identity for the dead. The first artifacts placed in the pit were spears and above them was a group of cauldrons, a bucket, shield, bowl, bag, and horse harness fittings. Once these items were in the grave the coffin, containing the body of an adult male accompanied by a sword and a purse, was lowered on top of them. A comb was placed on top of the coffin before attention shifted away from the main grave. A horse was sacrificed and buried in a second pit around 1 m away. After this event the main mound was constructed to cover both pits. Thus, the mound 17 funeral would have involved a complex set of performances around the structured display and concealment of the body and artifacts, with the process being indexed by the construction of the mound.

The preceding discussion has concentrated on the “positive” aspects of memory. However, memory can also be a problematic experience. Borić (2010) has noted the personal and social costs of remembering traumatic events. In particular, he has noted the difficulties in dealing with the excess of historical memory in the countries of the former Yugoslavia. Jones (2007) also considers this point; drawing on the work of Michael Stewart, he points out how strategies for dealing with traumatic social memories can vary dramatically from group to group. Both the Jews and the Roma experienced the Holocaust. In contrast to the well-documented commemorative practices around Holocaust memory in Jewish culture, the Roma do not explicitly “commemorate” the events. Rather, Stewart argues, Roma groups externalize these difficult memories by situating them in their interactions with wider society. Therefore, these memories are physically indexed by a whole suite of material culture associated with the boundaries between Roma and non-Roma society.

Memories can also be deliberately suppressed, at both a personal and group level. There are good archaeological examples of this process, particularly around the role of iconoclasm in the deliberate erasure of memory. The Roman tetrapylon, or four-way triumphal arch, which stood at the center of the legionary fortress in Caerleon, Monmouthshire, UK, survived, along

with the fortress bath-house, as an intact structure into the medieval period. Ray Howell (2000) has shown that by the early thirteenth century these monuments had become directly associated with the growing literature around King Arthur. He argues that the simultaneous demolition of both of these structures was a deliberate act of iconoclasm arising from the disputes between Welsh and English lordships over the control of Caerleon. Pamela Graves (2008) provides a detailed archaeological analysis of the process of iconoclasm in sixteenth- and seventeenth-century England. This allows us to see deliberate practices of (enforced) forgetting, which closely parallel the practices of remembering we discussed earlier. Graves demonstrates how iconoclasts in early modern England had an embodied and material understanding of how certain “indices” in religious artworks acted within memory practices around traditional Catholic worship. The heads and hands of religious images were the most important trace or index in this process and, therefore, they were purposefully targeted by the iconoclasts. These fragmented images were then deliberately left on display. The images then functioned as a, literally, reformed index. Anyone encountering these images would then have been able to draw on both the original traces, their citation and rewriting by the iconoclasts, and the recapitulation of the original acts of devotion as an act of destruction. The reformed images would have been central to the new understandings of the past and the changing religious orthodoxy promoted by the iconoclasts.

An embodied and material approach to archaeologies of memory and remembrance can therefore be seen to be applicable at both a group and personal level, to cover both practices of remembering and of forgetting, and all of the postulated “levels” of memory from unconscious habit-memory to the most complex and discursive accounts of the past.

SEE ALSO: Bodies and Embodiment;
Environment and Landscape

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Mind and Cognition

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Mind and *cognition* are two terms interchangeably used by archaeologists trying to approximate past ways of thinking. Cognitive archaeology, or the archaeology of mind (as it is also called), is a sub-discipline that moves past post-processualism's preoccupation with *what* past peoples thought, by focusing on *how* they carried out their cognitive processes. While early such attempts can be traced back to the 1970s, "cognitive-processual" archaeology grew in the 1980s, becoming officially established at a conference organized by Colin Renfrew and Ezra Zubrow in April 1990 at Cambridge, UK. Since then, cognitive archaeologists and affiliated scholars have been able to account for multiple facets of prehistoric and historic minds, ranging from technological to ideological, linguistic, and artistic.

A major focus of discussion, since the 1980s, has been the evolution of the "modern" human mind. In order to illuminate the origins of cognitive modernity, scholars have set out to detect modern human behavior from archaeological proxies, such as composite tools, complex hearths, organized domestic space, long-distance exchange networks, fishing, mobility strategies, burials, cave art, figurines, and ornaments. While such evidence had been associated with the European Upper Paleolithic up until the turn of the millennium, the recent discovery of bone tools, engraved ochre pieces, and shell beads has pushed the appearance of behavioral and cognitive "modernity" back to the African Middle Paleolithic/Middle Stone Age.

These artifacts have already been used to make inferences about a range of cognitive processes. The technological capacities required for manufacturing and using tools were among the first to be studied, given their position at the starting point of the archaeological record, as well as the fact that they exhibit increasing

complexity over time. Most notably though, the archaeology of mind has been preoccupied with the capacity for symbolism. Imbuing the material world with arbitrary and conventional meaning is generally considered as a defining feature of the human condition because the storage of information outside the brain allowed humans to communicate their cultural values to others. As would be expected, this cognitive Rubicon has been closely linked with the appearance of modern language—another ability that has taken center stage in cognitive archaeology. Yet, besides symbolism and language, cognitive archaeologists have also studied various other capacities such as working memory, joint attention, visuospatial and abstract reasoning, long-term planning, self-awareness, theory of mind (i.e., the understanding of false beliefs and other abstract mental states, such as higher-order desires), and level-2 perspective-taking (i.e., the ability to inhibit one's own perspective and comprehend how an object looks from another person's perspective).

Being able to infer cognitive processes from the material record is without a doubt an ambitious endeavor. Cognitive archaeologists have long recognized that the meanings of past practices cannot be deciphered because "cognized" categories held by past minds cannot be directly accessed. This does not, however, render the material evidence incapable of shedding any light on the thought processes carried out by past peoples. On the contrary, the artifacts discovered by field archaeologists can prove particularly telling when examined under the prism of theories drawn from the philosophy of mind and cognitive science. Yet, the most suitable method to examine material culture has been at the center of much debate, especially since the turn of the millennium, when a new school of thought challenged the traditional take on cognition. Dissonance mainly stems from the contradictory ways in which scholars have been approaching two main issues: (1) How did past minds function? and (2) How did they come to be? As shall become clear in the following sections, the ways

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in which archaeologists have been studying the nature and evolution of cognition has proven an interdisciplinary affair of diverse forms.

The nature of cognition

Those invested in the origins of the human mind tend to automatically equate it with the prodigious brains of a selected few (e.g., Mithen 1996; Klein 2009; Henshilwood and Dubreuil 2011; Hoffeecker 2011). This sort of methodological individualism, which locates cognition inside the head, is inherently engrained in the Cartesian and computationalist way of thinking that has long dominated the sciences. It is generally taken for granted that a brainbound apparatus collects input from the world, in order to construct symbolic representations that are, in turn, used in the computations underlying cognitive tasks. These mental operations produce internal templates that are subsequently materialized into the external world by way of deliberate behavior. Seen through the prism of representational nativism, Middle Stone Age shell beads such as those discovered at Blombos Cave are generally treated as the epiphenomenal products of symbolically capable brains, that intentionally imbued them with symbolic meaning, in order to communicate personal and social information to others (Kuhn and Stiner 2007). Associating material culture with the representation of predefined notions, cognitive archaeology has been—from the outset—largely preoccupied with a representational mechanism linking mind and matter.

This representationist take on the relationship between mind and matter cannot, however, explain how the brain can know aspects of the world prior to their empirical instantiation. In addressing this issue, Renfrew (2001) proposed that concepts arose in unison to their physical manifestations, as is, for instance, the case with the concepts of “weight” and “value.” Given that these kinds of meaning depend on more than the individual, he placed the foundations for a paradigm shift that treats cognitive systems through an anti-representationalist lens. From an empirical point of view, concepts are actually grounded on concrete experience; and since much of everyday thinking takes place through

our skilled engagement with the physical world, it would be mistaken to reduce the “cognitive” to the “symbolic.”

In light of the “internalist” dictum’s shortcomings, an “externalist” wave of cognitive archaeology has come to extend the boundaries of cognition beyond the confines of the braincase (e.g., Knappett 2005; Malafouris 2013). In fact, according to a theoretical framework known as Material Engagement Theory (MET), it may be better to speak of the mind as having no location whatsoever (Malafouris 2013, 85). For its proponents, cognition is actually brought forth through an intricate dialectic process between brains, bodies, and things. Rather than granting the brain with ontological priority, MET has been making a case for the priority of material engagement. Against the view that sees material culture as a premeditated invention, the theory of material engagement attributes its creation to a process of enactive discovery. Adhering to a novel theory of cognition known as enactivism, this theoretical framework posits that, instead of representing the world, humans amass knowledge by using artifacts to probe their environments. Given that these objects do not just incite, but actively shape the very forms of human thinking, scholars subscribing to an enactive sensorimotor account consider the material world a constitutive part of cognition. From the vantage point of MET, artifacts, such as the aforementioned beads, are not the epiphenomenal products of symbolic templates, but the material scaffolds required for the realization of significative and especially, symbolic ornamentation (Iliopoulos 2016). As we shall see in the following section, reconceptualizing the relation between mind and matter is closely linked to a reconceptualization of cognitive evolution.

The evolution of cognition

The evolution of the human mind has been mainly studied from a Neo-Darwinian perspective, which attributes our unique cognitive abilities to neural advances of adaptive relevance (e.g., Mithen 1996; Klein 2009; Henshilwood and Dubreuil 2011; Hoffeecker 2011). According to the archaeological consensus, looming ecological

problems, such as changing environmental and demographic demands, are responsible for exerting the selection pressures that drove the development of adaptive behavior and cognition. This assumption leaves room to neurocentrism, according to which artifact-related concepts are first processed by homuncular systems at the subpersonal level, and are then transferred into awareness at the personal one. Only once bestowed with an evolved mental architecture were modern humans able to deliberately produce an array of cultural practices for the purpose of addressing the impending need to transmit cultural information to a greater number of people. The rate of transformation from archaic to modern human beings has been widely debated, with some scholars arguing that modernity was the result of a sudden break with earlier behavior, others favoring a more gradual and mosaic development, and still others arguing that innovations are not restricted to our species and appear and disappear in Africa, Europe, and the Near East between 200,000 and 40,000 years ago before becoming fully consolidated. Despite their differences, most scholars seem to agree on attributing cultural innovation to prior biological evolution, essentially making a clear distinction between the two trajectories. As they see it, the former is the epiphenomenal product of the latter because function is purportedly preceded by structure. From this neo-evolutionary point of view, the appearance of artifacts such as the Blombos beads has been attributed to prior structural reorganization and expansion of particular cortical areas (Henshilwood and Dubreuil 2011).

This tendency towards biological reductionism has been recently critiqued on the count that the interaction between biological and cultural entities is much more fundamental than commonly assumed. According to recent developmental perspectives (e.g., developmental systems theory, probabilistic epigenesis, and neuroconstructivism), biological and cultural evolution are intimately entwined dimensions of the same ontogenetic process. For the proponents of these post-genomic metatheoretical models, social practices are not the transcribed products of genetic or cultural codes—they are instead the dynamic catalysts and products of complex

developmental processes that involve bidirectional influences within and between genetic, neural, behavioral, and environmental levels of analysis. In this light, social scientists have started replacing the linear and genetically deterministic stance towards evolution with an ontogenetic or developmental approach.

From the long-term societal perspective of archaeology, the theory of material engagement has focused on tracing the diachronic ontogenesis of the human mind (Malafouris 2013). Drawing from developmental neuroscience, its proponents posit that the neural substrates of cognition are amenable to continuous change. Given the remarkable plasticity of the human brain, MET refutes the prevalent notion that it has remained the same since speciation. In fact, not only has this organ changed much over the past 200,000 years, but also its constitutive entwinement with material culture has shown great diversity. According to Malafouris (2013, 46), the embedment and inextricable enfoldment of our plastic mind in a plastic culture may well be the defining trait of our species. Doing away with the notion of *modernity*, MET urges cognitive archaeologists to explore this system-wide *metaplasticity* by tracing the ongoing evolution of historically situated ways of thinking. To return to our case example, the significative concepts associated with the aforementioned beads were not envisaged by already evolved brains; they were instead brought forth through long-term processes of material engagement (Iliopoulos 2016).

Future directions in research, theory, and methodology

In moving away from the relativist agenda of post-processualism, cognitive-processualist archaeologists set out to develop a rational methodology that would allow them to use artifacts in order to infer properties of past minds. Yet, despite aiming towards a universal method, the field evidently took quite distinct forms. Until recently, it was the Cartesian and neo-Darwinian dictum that drew the lion's share of attention. In fact, such was the automatic predisposition of scholars towards a dualistic and deterministic outlook that it was often assumed without

explicitly considering its theoretical implications. It should come as no surprise though that carrying through with the bold task of accounting for entities as elusive as past minds requires an empirically supported and analytically precise epistemology. This framework should be able to use the archaeological record in order to infer behavioral systems, which it can in turn link to mental and eventually neural systems (Garofoli and Haidle 2014).

To connect artifacts with behaviors, minds, and brains, archaeologists must draw upon the theoretical and experimental findings of other areas. As we have seen, transgressing the boundaries of archaeology has already provided us with the analytical tools required for studying the biological, social, and cultural foundations of the human mind. Delving further into the study of past minds can veer towards many fruitful directions. For one, the thought-and-action processes required for the manufacture and use of tools can be identified by coding the physical actions involved in their construction into sequences of operational units depicted in “cognigrams” (Haidle 2012). Studying the origins of material signs, on the other hand, would necessitate a semiotic analysis of behavioral systems. By employing a rigorous theory of semiotics, cognitive archaeologists will not just be able to describe the perceptual and conceptual interpretations of past peoples; they will also be able to account for the evolution of material signification from physically founded to entirely arbitrary meanings (Iliopoulos 2016). The semiotic capacities gleaned from archaeologically visible behaviors can in turn be mapped onto neurocognitive systems. The neural architecture required for supporting different kinds of thinking can be explored by integrating the theoretical and experimental findings of neuroscience into archaeology (Renfrew et al. 2008). This collaborative platform, known as neuroarchaeology, has already employed neuroimaging methods in order to address the development of practices that are especially pertinent to archaeology. A materially sensitive neuroarchaeology thus appears to be a promising route towards understanding how various artifacts incited and shaped the thoughts carried out by past peoples, as well as for tracing how the synergistic fusion of their brains, bodies, and things changed while they

were traversing through distinct spatiotemporal trajectories.

SEE ALSO: Bodies and Embodiment; Creativity; Evolutionary Theories; Interpretation; Knowledge and Inference; Making and Skill; Material Agency; Material Culture; Material Entanglement; New Materialisms; Perception and Experience; Personhood and Objecthood; Substances and Materials; Symmetrical Archaeology; Time and Temporality

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New Materialisms

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New materialisms is the term used to describe a variety of theoretical approaches that share a commitment to the importance of “the material” in our world. New materialisms differ from traditional materialist, and particularly Marxist, approaches in their commitment to an alternative understanding of the nature of matter. The approach is relational (see *ASSEMBLAGE* and *SYMMETRICAL ARCHAEOLOGY*), emphasizing the ways in which materials, people, things, animals, plants, and places are the product of their relations and their properties, and potentials are defined by these relations. The understanding of matter adopted by new materialists has a range of consequences for agency, the position of humans within our ontologies, the role of dualisms, and how we understand history, change, and cause and effect.

In traditional approaches, matter is viewed as an inert substance—the brute, dead, solid foundation of the world around us. This position, drawing on Descartes and Newtonian physics, suggests that the solid world of matter is quantifiable, bounded, and static. Matter does not move or change without the application of another force; it is predictable and controllable. Coole and Frost (2010, 8) term this the Cartesian–Newtonian understanding of matter. In contrast, new materialists adopt a stance, drawing on both philosophy and the increasingly complex views of what matter is, and is not, which are emerging from the natural sciences, to argue that matter is lively and ever-shifting, capable of change without the need for outside forces, unpredictable and uncontrollable. Matter is not static and nor is it clearly bounded in new materialist approaches.

The traditional view of matter has led to a position where humans are seen as exceptional. Matter is portrayed as passive, predictable, and controllable, whereas humans in contrast are active, rational, unpredictable beings with their

own agency (see discussion in Coole and Frost 2010, 7–8). It is humans who have the ability to change the material world around them and impose their will on a blank canvas of materials. It is also humans, who, through our ability to measure and describe matter, are able to understand the world around us. If, however, we adopt the new materialist stance on matter, that it too is lively and unpredictable, then the position regarding agency also shifts. Bennett (2010), for example, takes a vitalist position and advocates that we recognize what she terms “thing-power.” For Bennett, materials are *vibrant*, by which she means always changing and in flux; they are equally capable of acting in the world. Bennett’s concept of vibrant matter gives us a sense of change that is not only the result of what is traditionally termed human agency, but instead comes from materials themselves which she views as never static, stable, or complete. Bennett and other new materialists are not just granting what is often termed, following Alfred Gell, “secondary agency” to materials; rather they are recasting agency completely. In Bennett’s work we see the role of trans-fats in the obesity crisis and a wildfire and company policy in an electricity blackout. Human agency, for Bennett (2010, Chapters 1 and 2) is just another case of thing-power.

Rethinking what, and who, might be capable of being seen as active in our world has clear consequences for ontology. New materialisms may be characterized as nonanthropocentric or even post-human, and proponents often state that they work from a “flat ontology.” In the Cartesian–Newtonian model of matter, humans occupy the ontological apex. It is humans who can measure and know the world, and thereby humans, and their attendant culture, have come to dominate and master the world of nature: Humans are the most important players in the world. Post-human and nonanthropocentric approaches argue that humans are only “one of many” who shape the world. Those who start their research from a “flat ontology” are happy for plants, animals, things, materials, and landscapes, as well as humans, to all emerge as agentive and

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potentially important in the narratives that they write. This does not deny or exclude a role for humans, but rather asks that we also give the rest of the material world its due. It also does not ask that we understand humans, animals, plants, things, and materials as the same; indeed, new materialists, drawing on the work of Gilles Deleuze, often revel in difference. Adopting a nonanthropocentric approach has clear consequences for blame and ethics and as a result it is viewed as radical and controversial by many.

The ontological position adopted, and the view that all matter is active and capable of change, results in a position that rejects dualisms, dichotomies, and oppositional thinking. By arguing that all matter is active, new materialists often reject a separation between the animate and inanimate. For many it also results in a rejection of divides between the organic and inorganic, sentient and nonsentient. DeLanda's work highlighting the flux inherent in geological strata illustrates the way in which it is not that matter is dead and inanimate; it is rather that we are not capable of perceiving the scale of this animacy. By disregarding the divide between the animate and inanimate and also adopting a nonanthropocentric approach, new materialists tend to avoid oppositional thinking entirely. In archaeological theory the questioning and rejection of dualisms and dichotomies reaches back to the influences of phenomenology on the discipline. For prehistoric archaeologists in particular, a reliance on Cartesian dualisms to explain the history of pre-Descartes periods has been heavily critiqued. The new materialist rejection of Cartesian dualisms is perhaps one of the reasons that the approach has come to appeal to many archaeological theorists; conversely, the rejection of the animate-inanimate divide can be seen as controversial and problematic by other archaeologists.

Adopting a new materialist approach has consequences for causation and, as a result, for how we approach history and change. For new materialists, cause and effect are not simply and unproblematically linked. Rather, the relational nature of the world and the animacy of matter means that causation is always complex and multiple. This is perhaps best explained by recourse to the concept of assemblage adopted by many new materialist thinkers. In assemblage theory the

world is understood to be made up of diverse, heterogeneous components such as things, people, animals, plants, and landscapes, all of which exist enmeshed within varied and multiple relations. Assemblages refer to the groups these components might find themselves in. Assemblages are always temporary and never fixed in either time or space—they exist at every scale, from the atom to the institution. Given that assemblages are complex, relational, interlocking wholes, simplistic, singular models of causation cannot be sustained (see, for example, Bennett 2010). As any given component within an assemblage is itself an assemblage, identifying a singular cause of any given event is not possible; instead causality is viewed as emergent and nonlinear, where any one effect becomes infused into other causes until cause and effect cannot be separated. Such an approach has clear consequences for the way we approach history and the way we understand change. The influence of new materialism on the ways in which archaeologists come to describe, interpret, and think about change and history is one of the key developing arenas that will define the impact of the theory on archaeology.

Consider Latour's classic example used to explore agency—a man with a gun shooting and killing another person. If we take a mono-causal approach, we might say the man is to blame, he is the cause of the death, and we should imprison him to reduce the risk he poses to the rest of society. We could take an alternative mono-causal approach and say that the gun is to blame and argue that if we reduce the number of guns in circulation we will reduce gun crime. Latour's point is that we need to take a relational approach—it is neither gun nor gun-owner that bring about the death, but the relationship between the two. Arguably, new materialists go further still as they reject singular and linear causation and argue for a role for a wider assemblage of components and their relations. Not only do we need to consider the gun but also the materials the gun and bullets are made of and the ways in which they have made a specific type of killing possible. It is not just the gun or even the bullet that "kills" but the failure of a heart to beat, of blood to reach organs, of lungs to inhale air, of oxygen to reach a bloodstream. Furthermore, the wider assemblage has played a role too: the actions of the deceased and by-standers, the attitudes and beliefs the

man held about guns, about justice and violence, his economic and social background, his job, his family and friends, and his specific motivations. A new materialist approach asks us to pay attention to all the different parts of the assemblage; it does not ask us to weight them all equally, but it does ask us to take them into account.

We can recast Latour's example as an archaeological one to bore into the role of materials further: Consider two people in the Bronze Age fighting with bronze swords. Bronze, as a material, opens up new possibilities—alloys can be melted and recast into a variety of forms in ways that stone cannot. The ability to cast shifts what shapes and types of objects it is possible to make. Metal alloys like bronze have specific properties; the molecules within bronzes can be hammered and cold-worked in order to make the lattice structure of bronze align better and as a result make the metal harder. As people learned of these properties, and began to work in concert with them, through the Bronze Age we see the development of an increasing variety of thinly bladed objects in a variety of forms such as daggers, knives, halberds, spears, and swords. The properties of bronze as an alloy and the understanding of the alloy that people had in the Bronze Age allowed the development of new forms of objects, which shifted what it meant to fight and kill in the period, and the way in which identities were understood. Rather than writing a narrative that focuses on human desire to control the material world, to make better weapons, and to fight, new materialists consider the role the material itself played in changing understandings and practices of combat.

By extending agency beyond the human and adopting a nonanthropocentric ontology, new materialisms have come to significantly question the privilege we give to humans in our explanations of the world. For new materialists, human culture does not master or sit above the natural world; rather it is part of it. This means that we cannot separate ourselves from the worlds we live within, or the worlds that we study. For critics, this recasting of humans as "one of many" and questioning of causality is seen as dangerous as it reduces our ability to seek justice or change the world. Conversely, advocates for the approach argue that only when we fully appreciate the complete cast of interlocking and connected

components in the world, and the complex causality that goes on, can we tackle the complex problems the world faces, such as climate change.

New materialism is part of what has been variously termed the turn to things, the ontological turn, and the material turn. This shift in theoretical stance could be seen as a reaction against the cultural turn, but is perhaps better understood as a supplement to it; it does not necessarily reject outright issues such as identity, meaning, and symbolism, but rather argues that a focus on the cultural without the material is not capable of understanding the complexity of our world.

For those outside of archaeology, new materialism is often framed as a response to the nature of late capitalism, where we are surrounded by the weight of materiality and the difficult ethical and political questions posed by advancing science and technology. Important changes in the way physicists understand the nature of matter have developed alongside increasingly complex and messy understandings about the "boundaries" between life and death. Key new materialist thinkers such as Jane Bennett, Karen Barad, Rosi Braidotti, and Manuel DeLanda draw influence from a variety of sources that include both the hard sciences and the humanities. Many of these thinkers are marked by a commitment to the political—a desire to change the way we conceive of, and shape, the world, often focused around inequality (there is a heavy influence from feminism) and the environment.

In archaeology, new materialism has arguably had the most influence in two forms: the adoption of assemblage theory (drawing on the Deleuzian inspired work of DeLanda 2016) and a re-engagement with materials and their vitality (drawing on Bennett 2010). Assemblage theory is having an increasing influence on archaeological theory (see, for example, Hamilakis and Jones 2017, and papers therein).

Arguably, the engagement with the vitality of matter began for many archaeologist with the work of Tim Ingold (2007), whose early repost to theories of materiality which focused on the human opened the door to approaches that moved beyond anthropocentrism and showed the ways in which materials are always shifting and never static. Ingold's questioning of the "hylomorphic model," whereby making is understood as the imposition of human agency and design on

dead material, has been influential in archaeology. The work of both Chantal Conneller (2011) and Andy Jones (2012) exemplifies the renewed focus on the role of the material in archaeology. Conneller's (2011) work considers the ways in which the properties of materials affect how they are worked and exploited by humans. Her work reveals how different communities have different understandings of the properties of a given material and thereby exploit them in different ways. Jones (2012) argues for the key role materials play in the performance of meaning in prehistory. Rather than viewing materials as simply something upon which human will and meaning are imposed, he argues, through a series of case studies, that the materials themselves played a key role in the creation of meaning in the past. Both Conneller (2011) and Jones (2012) effectively, and productively, bring together the work of material scientists and specialists with archaeological theory.

There are a number of key issues at stake that will affect the future role of new materialisms in archaeological theory and archaeology more broadly. Chief among them is the issue of nonanthropocentrism and the adoption of a post-human ontology. For many archaeologists, archaeology is defined as the study of the *human* past through material remains, and, as such, the suggestion that archaeology should become nonanthropocentric seems an affront to the nature of the discipline (see, for example, the critique in Van Dyke 2015). Nonanthropocentric approaches have also provoked criticism for a perceived failure to appreciate human difference, engage with social justice issues, or consider the role of power in the narratives they write. The radically different understanding of the world that drives the new materialisms, and in particular the place of humans as one-of-many in their ontology, is likely to remain controversial. This problem is compounded by the variety of theories, theorists, and philosophical positions that fall under the term new materialist and

the differing emphases they place on humans, resulting in differing archaeological narratives (see, for example, Witmore 2014 and the response from Ingold). Within the general field there are those that practice a wholly recognizable form of archaeology (see, for example, Conneller 2011; Jones 2012) and others (for example Witmore 2014) who are calling for archaeology to become a radically different subject less concerned with the human past and more concerned with the study of objects.

SEE ALSO: Material Culture; Substances and Materials

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Perception and Experience

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Since the early 1990s, the ways in which people perceived or experienced prehistoric material culture and landscapes both in the past and present has come to the fore in archaeology. Research in this area has attempted to gain an insight into what life may have been like, primarily during prehistory, through our engagement with sites, landscapes, or artifacts in the present day. Before looking at how archaeologists gain an insight into our engagement with such seemingly intangible phenomena we must first define what we mean by experience and perception.

Experience can be defined as the acquisition of knowledge relating to phenomena through our exposure to, and interaction with, the phenomena in question. For instance, the accumulation of knowledge relating to phenomena could be gained through continual exposure to a landscape. By inhabiting the landscape over extended periods of time, and experiencing it at different points of the day, and during different seasons and weather conditions, one might be able to gain insight into how people interacted with this landscape in the past.

Perception deals with our relation to phenomena through the uses of our senses. While studies in archaeology have primarily focused on the visual elements of perception, perception encompasses all of our senses. The combination of sensorial inputs is our perception of a phenomenon, and so, for instance, haptic approaches to material culture have emerged within the discipline. In other words, both perception and experience are contingent on bodily engagement with the object of our study.

The primary approach to this kind of study in archaeology has been through the utilization

of the branch of philosophy, phenomenology. Edmund Husserl is regarded as the first modern-day phenomenologist, with the likes of Martin Heidegger and Maurice Merleau-Ponty building on his work. Each philosopher had their own approach to, and understanding of, phenomenology. In each case, all were concerned with understanding the nature of subject–object interactions and how our material engagement with the world helps us to make sense of them, or ourselves.

In brief, Husserl's approach centered on a desire to get “back to the things themselves” and, through moving perceivers from their natural to phenomenological attitude by means of the transcendental phenomenological reduction, Husserl believed perceivers could suspend their knowledge of the natural world and reduce their experiences of phenomena down to their essential characteristics. Heidegger and Merleau-Ponty both rejected the transcendental approach to phenomenology, believing that our understanding of the world is interwoven with our personal experiences of it and that phenomena can only be understood within the context to which they are unveiled to the perceiver. Through the use of hermeneutics, Heidegger sought to understand a perceiver's engagement with the world through a more interpretative account. Merleau-Ponty, whom many archaeologists use as a starting point, attempted a third way of looking at the world, seeking to break away from the subject–object dichotomy and bridge the division between an empiricist (see *EMPIRICISM*) (Heidegger) and intellectual (Husserl) way of looking at the world.

Here, we define phenomenology as being a descriptive account of a phenomenon as unveiled to, and experienced by, the perceiver. Understanding the essences of our perception and experience allows us to better understand the phenomena. It creates a deeper connection with the phenomena and *may* allow us some insight as to what life could have been like in the past. However, how this might be translated into useful archaeological narratives is much contested.

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Insights into how people in the past interacted with monuments and objects through experience and perception are the primary way that phenomenology has been used in archaeology, although it has also been utilized in ontological contexts. Experiential approaches to doing archaeology emerged in the first half of the 1990s in the work of post-processual archaeologists such as John Barrett, Matthew Johnson, Julian Thomas, and Michael Shanks, all of whom were interested in embodied and sensory approaches to monuments in the past and the present, based on the premise that architecture controls bodily movement in socially conditioned ways; exploring or replicating those experiences thus enables an insight into past social conventions, rules, and power structures. Not all of these studies were phenomenological, but all explicitly relied on an embodied and engaged approach to experiencing Neolithic monuments or castles, as opposed to traditionally used approaches (such as access analysis and map work) which depended on a detached stance.

The first attempt to set out a detailed theoretical and methodological framework for phenomenological experiential approaches was undertaken by Christopher Tilley (1994), who argued that archaeologists could “suspend their knowledge” when in the field, and give primacy to the role of the body and the senses in navigating and interpreting archaeological sites and landscapes. Drawing on philosophers Heidegger and Merleau-Ponty, Tilley established “landscape phenomenology” as a fieldwork methodology, illustrated through a series of extended case studies drawing on walks and personal accounts of the impact experiences with Neolithic monuments and their localities had on his senses and body. Subsequent refinements of this method broadened the temporal and material boundaries for the use of phenomenology in archaeology, but in essence Tilley’s approach involves giving primacy to subjective perceptual observation as a means by which past motivations and experiences can be evoked. The process ends with interpretation of the experience of body and senses of the archaeologist: “drawing together all these observations and experiences in the form of a synthetic text and imaginatively interpreting them in terms of possible prehistoric life-worlds ...” (Tilley 2008, 274).

Tilley’s landscape phenomenology remains a dominant and influential means by which perception and experience may be used in an archaeological context. Approaches that draw on sensory perception inspired by Tilley’s project have been much imitated, sometimes uncritically, but more often with various modifications, checks, and balances. The primary use has been to study Neolithic monuments across Europe, although phenomenology has also been applied to later prehistoric enclosures, Roman sites, castles, and historic landscapes. Proponents of such experiential approaches include Vicki Cummings, Aaron Watson, and Alasdair Whittle, with much of this research emerging within a northwest European context.

Experiential approaches to studying the Neolithic have been subject to sustained critique (Brück 2005). Fleming (2006) has been critical of the levels of rigor and repeatability within such fieldwork, while the nature of the interpretations made are problematic due to an inability to demonstrate causation, and contemporary bias towards the sense of vision. Barrett and Ko (2009) and Thomas (2006) have argued that landscape phenomenology misunderstands the phenomenological basis for the methodology and as used by Tilley is merely a means to walk about, describe what one sees, and interpret the results within specific historical conditions. These issues, as well as accusations of solipsism and modern-day antiquarian indulgence, and a recognized lack of sufficient granularity in environmental information to adequately replicate prehistoric landscape conditions, have helped modify, refine, and mitigate experiential approaches within archaeology, most recently with the use of digital technologies and geographic information systems (GIS).

Experience and perception have not been restricted to landscapes and monuments. Thomas has argued that “ideas of the phenomenological traditions have been highly influential in the study of material culture” (Thomas 2006, 43). Approaches that foreground how we use, interact with, and are stimulated by materials around us such as experimental archaeology, haptic studies, and approaches that consider the manufacture and use of objects subvert typological empirical studies by foregrounding experience and sensory engagement with things.

Experiential approaches to monuments, buildings, landscape, and material culture are now commonplace in archaeology and to an extent a given, having evolved beyond the theory-laden approaches prevalent in the 1990s and 2000s, and with less emphasis on the philosophy of phenomenology. Concepts such as a sense of place, biographical and spatial approaches to landscape, and issues related to materiality and the elements have all emerged because of the experiential turn in archaeology in the early 1990s.

While phenomenological investigations have been undertaken within archaeology since the late 1990s, as of yet there is no widely accepted methodology or guide for best practice. There are, however, several approaches that allow us to gain an insight into how people may have perceived and experienced prehistoric objects, sites, landscapes, and monuments.

Perhaps the clearest defined methodology for experiential archaeology has been refined since the early 1990s by Tilley. In *A Phenomenology of Landscape*, he introduces a first-person account of walking the landscape by means of the Neolithic Dorset Cursus in southern England (Tilley 1994, 173–196). For Tilley, walking allowed him to begin understanding the position of monuments within the landscape, looking at views to, and from, a monument, partially replicating prehistoric bodily experiences. What his account lacks is any clear fieldwork methodology or structure for recording his experiences. Hamilton et al. (2006) provide a more robust and structured method for walking a landscape by means of their phenomenological site catchment analysis (PSCA). PSCA participants walked one hour in each cardinal direction noting changes within the landscape and ground conditions using recording pro forma; experiments with group participation were attempted, as well as a gendered reading of results. This methodology also incorporates the use of 360° diagrams, the use of which is adapted from Cummings and Whittle's 2004 study of barrows and landscapes in Wales, and drawn by participants in order to record what they could see from a set location (usually an archaeological site), and establish patterns, although such devices prioritize visual perception.

Other sensory experiences have been given less attention. Hamilton et al. (2006) sought to understand how everyday sounds and smells may

have been experienced within Neolithic ditched enclosures, while Keating and Watson (1999) have researched the sensorial effects of sound within passage graves and stone circles, part of a growing field of archaeoacoustics. In these examples, the potential experience and impact of sounds in domestic and ceremonial contexts were considered, with, for instance, percussive sounds within megalithic tombs potentially having physical and psychological impacts on participants, causing altered states of consciousness.

The approaches and studies above do not claim to provide exact accounts of the experience of prehistoric people, but instead look to give an insight into how people may have inhabited landscapes (see *INHABITED LANDSCAPES*), or experienced monuments, during their time of occupation. Furthermore, as the experience of a landscape is different to that of a tangible object, the approaches to each phenomenon will inevitably be unique and personal. The value of such approaches, which happen in contemporary settings, remains open to discussion, but it is clear they offer a different perspective, open new lines of enquiry, and have been deeply influential.

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Personhood and Objecthood

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Within archaeology, a study of personhood may focus on what or who was considered to have the capacity of being *a person* in a given historical context. It examines how and in what manner *a person* was produced and articulated. Just as personhood relates to the state of being, or being regarded as, a person, objecthood describes the state or condition of being an object. In art studies, the term *objecthood* is applied, more specifically, as the opposite of *art*, from the art historian Michael Fried onward. The concept of personhood is also applied in psychological and philosophical studies of self and identity, and in law in relation to issues of rights (such as animal rights, etc.).

More than anyone else, Chris Fowler has introduced the study of personhood in archaeology (Fowler 2004). Fowler builds partly on the ethnography of Marilyn Strathern and Janet Hoskins and on Marcel Mauss's theory of reciprocity and gift giving. Ethnographic studies have demonstrated that very intimate links between the life stories or biographies of individual humans and objects may be produced. Strathern points out that gifts *are* relations, which means that, through gift giving, the social biography of objects and humans become interwoven (Strathern 1988). Personhood is fundamentally linked to relationality, in varying degrees and forms. Ethnography can be used to identify the multitude of ways in which personhood may be constructed in a given context, time span, or setting. In particular, the concept of *dividual* versus *individual* personhood has been highlighted in these studies. Whereas *individuality* is emphasized as part of modern, western concept of personhood, other cultural contexts, past and present, may be dominated by the idea that persons are not bounded but partible; a person

is a composite being, produced and expressed through actions such as gift giving (including the marriage exchange). A dividual person thus emerges from the relations *between* humans; and such a person may consist of substances (such as gifts) that are transmitted from one body to another (Strathern 1988).

Whereas a study of identity may investigate diverging and overlapping social roles and social interaction, a study of personhood aims at examining questions of *ontology*. Studies of personhood have been criticized for relying too heavily on specific ethnographic models. However, it is crucial to understand the ethnographic parallels as models that are what Claude Lévi-Strauss would qualify as *good to think with*. They are alternatives to a modern, western concept of personhood dominated by the idea that one human body equals one individual, which in turn equals one person. The study of personhood is thus not a theory to be applied to the archaeological material, but a way in which one may approach that body of material and raise research questions.

Within archaeology, the study of personhood has been of particular interest to research on Neolithic and Bronze Age Europe. Such research includes studies of the construction and deconstruction of personhood, as examined through analyses of fragmentation and wholeness in relation to burial customs and acts of deposition. As Fowler points out, a general feature found in many religions is the concern for the fragmentation of a person following death. In acts related to burial we find many examples of attempts to either preserve the integrity of the body or accentuate its fragmentation. In other words, burial acts underline cultural themes related to personhood. Research on personhood has actuated a stronger focus on the parallels between the way bodies and objects are treated, handled, and marked; recent studies have indeed clearly demonstrated the *changing* character of personhood in different cultural contexts. These alterations of personhood are also identified in relation to change of religion. For instance, the burial customs of the Viking age show the largest degree of variation

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observed in any prehistoric period of Scandinavia. These pagan graves contain profound examples of fragmentation and destruction of the body, but also burials that show extreme care to preserve the wholeness of the body and the grave goods. This changes with the advent of Christianity in Scandinavia: after this conversion the burial customs are still highly divergent, but all consists of *whole bodies* with *whole objects* in them, which points to a parallelism in the way bodies and objects were treated.

In many cultural contexts, be they of the past or of the present, personhood is not considered to be restricted to human beings, and concepts of objecthood diverge from modern western ideas of what an object is. Studies of human–animal relationships have showed that the modern western notions of personhood and objecthood may not be representative of past societies. In numerous circumpolar contexts, it is not solely human beings that are considered *persons*, but other types of beings as well, for example stones, trees, and animals. Among the Siberian Khanty, humans, animals, water running in a river, falling snow, or thunder are considered animate, whereas snow that has fallen, water in a bucket, or a rock that cannot be moved are considered inanimate objects (Jordan 2003, 103). These types of categorization of what it means to be a person or an object are also found outside the circumpolar areas, mainly among hunter-gathers such as in the Amazon, which shows noticeable similarities to the circumpolar examples (Brightman, Grotti, and Ulturgasheva 2012), and in the Andes (Sillar 2009).

Benjamin Alberti studied La Candelaria anthropomorphic vessels from Northwest Argentina—or what he terms *body-pots* (Alberti 2007). Instead of seeing these objects as *representations* or *symbols*, one may understand them as beings in their own right: not as humans, but as persons. Personhood may also be identified in archaeological contexts where objects were treated as if they were human bodies, since they had the same *capacity* as a human body. For instance, in a number of Norwegian cremation graves of the late migration period, a single bucket-shaped vessel, a unique object type, was placed in the grave and used as container for the deceased bones. While the vessel replaced the human skin, the person was preserved

through the transformational act of the burial (Fredriksen 2006). Such a perspective departs from interpreting these objects as mere *representations* of human bodies. In many contexts, the personification of the object or a feature in the landscape is understood as *occurring* in specific situations. Thus, one way of approaching personhood versus objecthood may be to turn our attention to objects and landscape features that, in specific cultural contexts, were treated, handled, and categorized differently from objects and landscape features in general. It must be recalled that this by no means implies that all animals and objects are considered as having personhood. Noticeably, in ethnographic studies of animistic hunter-gather societies, personhood emerges *in the given context of a specific time and place*. A tree or an animal is not considered to simply *take the role* of a person, but to *be* a person. This implies that a western ontology of personhood is not necessarily applicable to other cultural contexts. Put another way, the ontological duality of nature and culture might not be relevant if we aim at understanding the mind-sets, worldviews, and ways of life of people from outside a modern or postmodern western world—and perhaps not even from inside it.

The study of personhood also relates to the concept of animism, because in animism specific natural features, animals, or objects may be considered to possess personhood. However, studying personhood is not in any way limited to societies with an animistic religion. Phillip Descola presents four different types, classes, or basic sets of ontologies, and one of them is an animistic ontology; but he points out that these ontologies, different as they may be, are not mutually exclusive (Descola 2013, 129–43, 231–3). Thus, even though people in western societies may treat their pet, their car, or their leather jacket as if it possessed personhood, that is not the expression of an animistic religion. As the social identity of objects is linked to the chains of social relations to and among humans through the social life of the object, the biographical perspective partly coincides with these perspectives on animism. In animism, reciprocity is a central element in the relationship between humans and objects, or humans and places. In the Andes, for instance, offerings and daily work

are used to develop reciprocal social obligations with animated objects and places. In this process humans create social relations with the material world. Furthermore, this relation imbues the implicated artifacts and places (Sillar 2009, 367–74).

New perspectives on objecthood have been brought to the fore by the so-called object-oriented ontology. Whereas the studies of personhood have a focus on potential agency (be it primary or secondary), object-oriented ontology rejects anthropocentric positions by placing emphasis on the fact that reality exists without human beings. Instead of examining only the effect objects have on humans, object-oriented ontology focuses on objects themselves, including their effects on one another. This position has developed in philosophy and has had a significant impact on contemporary art. Just like the research on personhood, these object-oriented approaches have had their focal point in ontology. One position that has absorbed these perspectives on objecthood in particular is symmetrical archaeology. The ontological turn has also been widely debated in anthropology, but object-oriented archaeology has emphasized the methodological differences between archaeology and anthropology; archaeology, in contrast to anthropology in practice, is (at least partially) a study of objects in which archaeologists, through the practice of excavation, engage with the material world in very specific manners. In symmetrical archaeology a key issue is that humans and nonhumans should not be regarded as ontologically different entities. Instead every being in the world can equally be seen as a differentiated thing (Olsen and Witmore 2015). Symmetrical archaeology has challenged the a priori anthropocentric stance of archaeological research. These perspectives have primarily been used in studies of contemporary archaeology. They focus on the qualities that objects or entities have and on the relationship *between* things, including the entanglements and assemblages of things (see Olsen and Witmore 2015, with references). Correspondingly, other studies have emphasized entanglements of humans and objects and the creation of entities in assemblages. By paying attention to the importance of *relations* between things and to the (continuous) construction of

entities consisting of objects and relations respectively, these studies have created new perceptions of objecthood. The turn toward objects has also been used to revitalize discussions in heritage studies on materiality, as even discarded, superfluous, and unwanted objects may be preserved through generations, thanks to their material persistency. More importantly, in ethics it has opened up a debate on whether things should be granted certain rights, including the right to decay (Pétursdóttir 2012).

SEE ALSO: Assemblage; Material Culture; Material Entanglement; Symmetrical Archaeology

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Philosophy of Science

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The philosophy of science

The philosophy of science is a subfield of epistemology, an area of philosophy that asks questions about the nature and limits of knowledge. Science focuses on a set of theoretical and methodological tools to study the natural world; and the philosophy of science studies the processes that lead scientists forward in their pursuit of knowledge. As in most philosophical disciplines, philosophical questions about science go beyond the stated expectations of their field of study. Here philosophers focus on the relationship between science and knowledge, on the goals of science (or of individual sciences), on the methods of science, and on the relationship between scientific theory and practice.

Perhaps ironically, the philosophy of science as a field has an indeterminate origin. Before the 1800s what we now think of as science was, to a large degree, tied more closely to answering philosophical questions than it was to experimentation. In fact, many early practitioners were called “natural philosophers.” The paradigmatic, lab-coat-wearing experimentalist is a product of the modern era, and indeed the name “scientist” was only given to this group (and to the world) in 1833 by William Whewell. As a result, there are those in the philosophical (though no so much in the scientific) community who question whether pre-nineteenth-century activities should be considered science (and whether their study should be founded in the philosophy of science). That being said, many philosophers of science specialize in medieval and ancient “science,” and, even among contemporary period philosophers of science, most agree that the tools used by philosophers of science can be applied to the ancient, medieval, and modern

worlds as readily as they are to the contemporary world.

Setting aside origin stories, traditionally the philosophy of science focuses on a number of core areas, namely questions concerning the separation of science from nonscience (the demarcation problem), questions about the theoretical foundations of science (explanation and confirmation), and questions surrounding the workings (methods) of science. As we will see here, each of these issues is as open a topic in archaeological circles as it is to philosophers. However, many in the archaeological world are unaware of the existence of these philosophical issues and, sadly, philosophers are generally also unaware of the work archaeologists have done to address them.

The demarcation problem asks where we are justified in drawing a distinction between fields that should be considered sciences and fields that should not. This job is difficult because there is no simple litmus test to divide science from nonscience. If we argue that science, unlike nonscience, is true, then we have to explain why Newton was not a scientist (as he was wrong about many things). Additionally, arguments based on the existence of data fall flat, as multiple fields, some of which are sciences (such as chemistry) and others decidedly not (e.g., alchemy), might share the same data set. Further, fields can gain or lose their scientific status as our ideas about science change, as was the case with parapsychology, once regarded highly enough as a science to command a section in Alan Turing’s 1950 paper on artificial intelligence, but now regarded as pseudoscience.

Perhaps the easiest way to demarcate science from nonscience would be to ask for a strict definition of science. However, sciences range in their focus from the strictly theoretical to the ultimately practical. They take place in the laboratory or in the field. They hold sway over matter subject to determinism or free-willed humans. This being the case, attempts to give a singular, unified definition to science have, to date, been

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largely unsuccessful. In response, some philosophers have offered solutions to the demarcation problem by creating lists of scientific criteria or desiderata, in other words Schick and Vaughn's (2013) testability, fruitfulness, scope, simplicity, and conservatism. Others see science as the means to understand how individual acts can be viewed as examples of universal laws (Hempel 1966). Still others show how easily science can be ruined by overconfidence and propose that the only real way to see whether something should be considered good science is to subject it to grueling tests designed to make it fail (Popper 1963).

Of course, every one of these options carries with it different assumptions about what scientists are doing when they don their white lab coats. When philosophers ask questions about the fundamental goals of science, these questions fall under the headings of explanation and confirmation. Scientists appeal to explanation in order to answer "why" questions (e.g., why my pencil drops to the floor when I release it from a height of two meters). To answer such questions, early scientists focused on inductive methods in their scientific approach (appealing to the relative sufficiency of evidence as a standard for scientific arguments). Others, including Hempel, believed that sufficient proof is not enough as a grounding for scientific certainty, arguing instead that science is, at its best, deductive (it appeals to logical certainty as the standard of evidence for arguments). Throughout his career, Hempel argued that the goal of science is to go beyond what he called "mere description." Instead, science should have as its purpose the explanation of phenomena. According to his account, explanations are the byproduct of using logic to ground scientific observations in universal laws. Once an observation is properly encoded, a scientist can not only explain a past observation but also predict its next occurrence. For instance, there is a real difference between documenting a pencil's falling and explaining its occurrence. By understanding the universal laws at play (gravity, friction, etc.) and the facts on the ground (a pencil being dropped from a height of two meters), I could explain the fall of the pencil, predict future falls, and show that other objects of similar mass and similar relevant physical properties will behave in the same way.

Once these explanations are set out, they can be put to the test, either against themselves or against other possible explanations. This activity is called confirmation; and, together, Hempel's models of explanation and confirmation were used to provide a foundation of certainty to scientific inquiry. If science is based on logically connecting individual events to universal laws, scientists would be able to fully understand the world, make certain predictions about the future, and fully confirm their hypotheses.

Unlike in the traditional "law and order" approach to science, other figures have argued that science cannot get to the truth of the matter by focusing solely on universal laws. According to Cartwright (1983), while laws may play a necessary role in explanation by setting order to chaos, we have no way of knowing whether these laws are truly real or universal. Kuhn (1962) argued that scientists divide the world up to answer questions that interest them, and create laws to help make sense of these divisions. For Kuhn, understanding the material behind our decision making is paramount if we are to make sense of scientific practices. Kuhn argues that scientists are a community that shares a worldview: literally, a particular way of understanding their topic, also known as a paradigm. This common language and understanding of the world is a precondition or a foundation for science. Paradigms unify a field, allow progress, and determine what is or is not to be considered science. It is only after we know which questions are good scientific questions that we can engage in the activity of doing science, an activity that Kuhn calls "normal science" (or puzzle solving).

While Kuhn founded science within the workings of the scientific community, other philosophers of science pushed back even harder against traditional science, arguing that shared worldviews cannot simulate objective truth; this led to an "any explanation goes" world. While some believe that the world itself is quite capable of telling us which explanations are plausible and which ones should be dropped, others, including Feyerabend (1975), have argued that, since shared worldviews are subjective, science itself is just a subjective ideology.

In order to unpack this problem, we need to look more closely at the worldview material undergirding our science. To some, this means

focusing on our values as scientists. “Science and values” questions ask about the impact our values (needs, desires, etc.) have on our science. Granted, not all values are considered appropriate to all scientists. While logic and certainty are considered to be perfectly acceptable epistemic values by the scientific mainstream, other, nonepistemic values may also play a part in our science. Sometimes this is a good thing. We value preventing suffering. So, for the most part, we do not run experiments that knowingly cause suffering in our test subjects. This is a choice that we make, however, and it does have consequences. There have been periods in history when the scientific community has questioned whether it should be able to use the data taken from inappropriate scientific experiments (experiments involving torture, genocide, etc.). Scientists in favor of using those data make arguments that saving lives now is more valuable than the value we place on doing and participating in responsible science. In other cases, scientists have to deal with unconsciously held values, ones that may or may not be truly detrimental to good scientific practice. For example, we could ask whether our views on gender shape our science. Or is it mere coincidence that science is defined by objectivity and reason, traits associated with the dominant group of scientists in the twentieth century—men? Similarly, those of us who live in the United States are certainly lucky, as capitalism (which focuses on individual discovery and competition) just happens to match up with the way in which we believe science “must” be done.

Philosoph(ies) of archaeology

Although there are people in the field who question whether archaeology should be characterized as a science and place it rather within art history or classics, most of the theoretical work from the mid-twentieth century to the present, the explicitly scientific nature of contemporary archaeological methods, and the existence of archaeometry (see *ARCHAEOMETRY*) as a field provide sufficient reason to argue that archaeology is itself a science. Furthermore, archaeologists working with artifacts and biological or environmental material benefit directly from work done

in other scientific fields (e.g., physics, geology, chemistry, biology, and anthropology). Fortunately, archaeologists have engaged, whether consciously or not, with many of the theoretical issues that dominate the philosophy of science. Hence the remainder of this entry will focus on connections between the philosophy of science and archaeological science.

Archaeological explanation and confirmation

While archaeology is, in one form or another, one of the oldest of disciplines, archaeological science is young. Before the mid-twentieth century, the goals of archaeology were associated with new ideas about culture that were coming from anthropology. That theoretical basis, called culture history, had as its goal the identification of distinct cultures or ethnicities by tying them to specific types of artifacts (material culture). Once a culture group was identified and established, it was believed that that group would remain stable and that cultural change (evident from changes in material culture) occurred through migration, diffusion, or invasion. In order to tie material culture to culture, Culture historians argued that a particular ethnic group could be inferred from, or associated with, a particular assemblage. They created master lists of ceramics, building styles, domestic animals, and even foods, and used these data to identify a site as belonging to a particular “people.”

Certainly, creating catalogues and understanding typologies is still important (and collecting archaeological materials remains an important part of fieldwork). However, a group of twentieth-century archaeologists argued that there must be more to archaeology than the cataloguing of finds. Abandoning the idea that cultures are rigid and easily distinguished through differences in diet, floor plans, or burial customs, these archaeologists, for example Binford (1962), believed that culture change is much more fluid. Binford had been reading contemporary work in the philosophy of science, and Hempel’s model of explanation and confirmation seemed like a good fit for this “new archaeology.” As argued by Krieger (2006), the new archaeology—later

renamed processual—attempted to map archaeology onto Hempel's nomothetic model of science. Processual archaeology would explain (and not just describe) the past by rooting archaeological fieldwork in general laws and deductive logic. Unfortunately, the new archaeology was unable to deliver on its promises. While the field attempted to set archaeology on the path to certainty and predictability, in the end, it got bogged down in the same systemic problems experienced by philosophers (asking whether useful universal laws of archaeology exist, questioning whether archaeological artifacts can be connected to modern explanations, and the like).

Critics of Hempelian processual archaeology, called postprocessualists, come in many forms, but they are united in rejecting the idea that the data are somehow objective arbiters of truth as well as processualism's narrow, law-based approach. In this rather Kuhnian view, also taken up by Marxist and feminist archaeological perspectives, archaeology can serve many purposes, depending on the worldview and goals of the excavator and sponsoring institution. Consequently, postprocessualists might focus on interpretations of data that favor underrepresented groups or tell multiple, potentially conflicting stories about a site, or they might decide to ignore archaeological data (as those data are going to be deposited by dominant groups) in favor of oral histories collected by the modern inhabitants of that site.

While it is true that culture history was replaced in the theoretical literature in the 1970s by processual archaeology, which was then attacked by postprocessual archaeology about twenty years later, this theoretical battle only exists on paper. Each of these positions, when removed from the hyperbolic rhetoric that makes for good academic papers but for lousy archaeology, contains a lot of potential for nuance and rapprochement with other positions. Just as we see in the philosophical literature, Hempelian-style (processual) and Kuhnian-style (postprocessual) archaeologies have evolved, incorporating materials from each other and making sense of the data in ways that best serve their values. Perhaps more interestingly, in the field, processualism and postprocessualism (and culture history) do more than exist: they coexist, as archaeologists, unconsciously or intentionally,

apply each epistemological foundation where they need it in order to address a particular sort of question. Fieldwork involves a huge amount of finding and cataloguing artifact typologies (culture history). Those findings are then routinely used in trying to learn about regional changes: large amounts of data are used to make us understand general trends about the site, region, or time period (processualism). Multiple perspectives are employed in order to construct and deconstruct canonical understandings of a particular ancient society by focusing on groups other than elites, such as the poor, slaves, minority groups, and the like (postprocessualism).

New archaeological frontiers in philosophy of science

While traditional questions about the nature of science play themselves out in archaeological circles, newer questions about the nature and limits of science have led philosophers of archaeology to bend the limits of their field. For instance, First Nations and other indigenous groups have challenged archaeologists' claims to the "ownership" of archaeological sites, artifacts, and remains. Where in some sites "traditional" archaeologists have fought to keep control of those sites and of their data, other archaeologists have instead engaged with native groups (see PUBLIC ARCHAEOLOGY). While deciding whether to create partnerships with local landowners seems like a purely political decision, deciding (as some have) to share curation of their data with oral historians and local communities and including outside interpretations of archaeological data in publications and excavation reports demonstrates how central epistemological issues are to these scientists. Recognizing the importance of collecting data about artifacts in context (which is crucial to an artifact's ability to be used as a piece of scientific data) but cognizant of the financial and political impact that archaeology has on peoples who live at (and off) a site, archaeologists are engaging with local subsistence diggers to find ways to preserve data and local lifeways while fighting the international black market.

Archaeologists are also looking to repurpose their data, employing new theoretical models

to break down the barriers between past and present. Where culture historians or processual archaeologists might have collected data for their own site (or maybe for larger regional studies about trade patterns), open access to archaeological data has allowed other groups to study, remix, and reinterpret old findings. Environmental archaeologists are also experts at sharing data, using material from ice cores and tree rings, appealing to climate scientists for their models, and then using those models to demonstrate the impact of environmental change on societies throughout time.

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FURTHER READINGS

Positivism

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Archaeologists have paid close attention to the philosophy of science in their search for epistemic and methodological grounds for their discipline. They have developed, within the archaeology realm, an interesting epistemic and methodological reflection. As Wylie (2002, xii) recalls, the training of young archaeologists included philosophy of science as well as specific research techniques.

Positivism, both in its nineteenth-century form and, particularly, in its twentieth-century neopositivist version, was a philosophical school of thought that played a key role in reflections on the nature of archaeological knowledge, as well as in the development of archaeological research approaches. It was at the heart of efforts to establish archaeology as a scientific discipline and has been the adversary with which the different post-positivist philosophical perspectives of post-processual archaeology have had to contend.

In the nineteenth and early twentieth centuries, the aim of North American archaeology was to gather as much data as possible in order to understand the past. Archaeology was a descriptive, taxonomic and inductive discipline linked to stratified chronology. The task of archaeologists was to establish data based on empirical observation, not to formulate laws and explanatory theories. Rather, they limited themselves to describing individual facts, on the basis of which they formulated stories to understand specific cultures.

In Europe, cultural narratives were explicitly interpretative in line with German historicism. Archaeology was part of history and, as such, interpretative prehistory. Archaeologists elaborated reconstructions of the past which were assessed according to the proponent's prestige (according to Thompson's authority argument (1956, 331), we evaluate reconstructions or interpretations by evaluating the competence of the person who is proposing the reconstruction).

These trends dominated the field of archaeology until the 1940s and 1950s, when they were called into question, mainly by North American and British archaeologists. To differing degrees, these archaeologists were advocates of neopositivism, which had emerged at the beginning of the twentieth century thanks to the work of Carnap, Neurath, Hempel, Nagel, Rudner, and Wallace, among others (including, of course, the Wittgenstein of the *Tractatus*). The basic aim of this philosophical movement was the analysis of language using mathematical logic. But it was mostly the neopositivist epistemology and methodology that archaeologists decidedly adopted. Consequently, between 1960 and 1980, the neopositivist epistemic approach was quite influential within the field of archaeology. Thereby, scientific research was considered neutral and objective, and expressed in observational language on which hypotheses and theories were tested—through either verification or, at the very least, confirmation. Observational and theoretical language constituted two different spheres; therefore, the terms used in each should be of a completely different nature. Finally, scientific explanation was based on laws according to Hempel–Oppenheim's deductive–nomological model—although inductive–statistical explanations were also considered scientific.

This was the epistemology of the “new archaeology,” also called processual archaeology, which constituted a dominant “research program” until the emergence of post-processual archaeology during the late 1980s. New archaeology first took form in a number of papers published after World War II (pioneering works included those written by Willey and Phillips (1958) and Taylor (1948)). The approach was later developed through the work of a group of archaeologists, headed by Binford (1962, 1968, 1977, 1979, 1987), with authors like Clarke (1968), Flannery (1968), Fritz and Plog (1970), Renfrew (1987), Watson, LeBlanc, and Redman (1971), among many others.

The basic thesis of this archaeological movement was that archaeology was not the mere descriptive study of archaeological sites, neither

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was it an interpretative history, as traditional archaeologists maintained, but rather science. As a science, archaeology was related to anthropology, of which it could be considered a branch—hence Willey and Phillips' (1958, 2) well-known rephrasing of Maitland's famous dictum: "American archaeology is anthropology or it is nothing."

Therefore, archaeology was considered a general science, based—just like any science—on observation, measurement, experimentation, generalization, and explanation. Since it was possible to objectively know the past and its laws, it was also possible to explain it and verify scientifically all this knowledge. While traditional archaeology focused on understanding specific cases, processual archaeology saw each individual case as being related to research of general issues. Binford described the new program in very clear terms (1968, 274): "We seek to replace these inadequate propositions with laws that are validated in the context of the epistemology of science, so that we may gain an accurate knowledge of the past."

The material base of new archaeology was archaeological records (see *ARCHAEOLOGICAL RECORD*), which contained direct and objectively observable, classifiable, and, therefore comparable, material remains. Although the cultures of the past had disappeared, they could be researched, since archaeological remains were records that could be observed and investigated. Thus, archaeologists organized their data and established typologies, taxonomies, temporal series, and integrative units (Willey and Phillips 1958, 5, 29–31). From these data, it was possible to infer facts and reconstruct the past processes, even though these processes could not be *directly* observed by archaeologists. This implicated formulating hypotheses regarding cultures' underlying processes, comparing them with those of other cultures, and generalizing. These hypotheses were checked by researching the material available in the present, and if they were verified, they became laws.

Processual archaeologists believed that research should focus on the organization and adaptive properties of cultural systems. The material remains found in archaeological sites were produced by societies that made up cultures, mainly as an adaptive response to the natural environment in which they developed. And, as

Binford (1979, 271) pointed out, "the research process therefore starts with the construction, usually from (cross-cultural) ethnographic data (see *ETHNOARCHAEOLOGY*), of a hypothetical cultural system and deduces the consequences of its regular functioning for the archaeological record." Culture is viewed as the extrasomatic means of adaptation for the human organism. Thus, new archaeology was not interested in the insides of action or the symbolic aspects of the cultures of the past (which were of interest to post-processual archaeologists), but rather in environmental determining factors, general mechanisms, and collective behavioral patterns. This is what enabled archaeology "to speak with greater authority and accuracy about the ecology of past societies, their technology, their economic basis and their social organization" (Renfrew 1987, 6).

Systems theory and evolutionism were the large-scale theoretical frameworks of processual archaeology. However, empirical research was not directly conducted from these broad frameworks, but from middle-range theories (MRT). MRT were formulated by Merton in the 1960s and were introduced into archaeology by Binford (1977). These theories were linked to empirical research and were located mid-way between observed empirical data and general theoretical frameworks. MRT enabled archaeology to be considered an experimental science. Processual archaeologists also used modern tools such as set theory, mathematical topology, the analysis of new geography, statistics, and computing (indeed, they were pioneers in the use of computation).

On the other hand, the processualists believed that researches showed that many innovations or cultural changes arose independently in a number of different, unrelated places, as well as at a number of different moments. Thus, they detected certain equivalences between existing "primitive" cultures and cultures of the past which occupied the same social-cultural and ecological niche. Analogies could be established between these two types of culture, and facts and processes could be inferred about the latter on the basis of research into the former. Analogies enabled general, verifiable hypotheses to be established, which, when proven, would become laws.

Laws were essential, since any archaeological explanation should be based on confirmed universal laws. The deductive–nomological model, which was based on covering laws, was considered to be the scientific explanation par excellence. This model was deemed to be the basic structure of any explanation. When no universal laws could be established, Hempel's inductive–statistical explanation could also be used.

As the 1980s progressed, the positivism of processual archaeologists gradually became more refined. There was an acknowledgment that the observational events in which archaeologists participated were partly the result of what they deemed profitable to observe. As pointed out by Binford (1987, 393), “Putting this situation very bluntly, all archaeological data are generated by us in *our* terms.” The existence of auxiliary hypotheses connecting data with the hypothesis to be confirmed through interpretations of these data was also accepted. But interpretative hypotheses should be confirmed; thus, if it is possible to conclusively confirm hypotheses of this kind, they could act as a premise of a deductive argument about that, given a particular kind of archaeological record, and certain specific conditions and events that must have occurred in the past.

However, processual archaeologists were extremely critical of post-processual archaeology and the various philosophical schools of thought that constituted it. They questioned the subjectivism, relativism, conventionalism, and textualism of these perspectives, along with their conception of culture as a system of intersubjective meanings involved in the actions. They also questioned the radical recourse to hermeneutics, that is, the idea that access to artifacts is determined by an adequate understanding of cultural context, and the consideration that archaeologists' observations were pre-intellectualized understandings, just as in the case of ethnographers and their intercultural experiences. Processual criticism highlighted the similarities between these positions and those adopted by traditional archaeology.

Processual archaeologists continued to maintain that recourse to experience was a key part of archaeological research: “At this juncture the scientist is responsible for seeking out experiences

as widely as possible in order to provide reality checks on the accuracy and utility of his ideas” (Binford 1987, 62). They did not stop believing that experience was independent from the hypotheses, that the external world existed—including the properties of archaeological records—and it was scientifically cognizable. They continued to propose explanations regarding the nature of the organizations of the past and how and why they changed. Thus, the fundamental aspects of processual archaeology remained active, despite the nuances introduced by the increasing influence of post-processual archaeology.

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Quantification and Social Life

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Quantification, measurement, and the quantitative idiom

Despite real differences among the theoretical approaches used by archaeologists to conceptualize the past, our research nevertheless is fundamentally concerned with understanding the social lives of past peoples. We seek to take the “static” archaeological record—the materials recovered from surveys and excavations—and translate them into the “dynamics” of a once vibrant cultural system.

“Social life” covers a great range of behaviors, structures, and processes; it includes everything, from foraging choices to kinship and from the division of labor to household consumption, political economy, and the formation of complex polities. As societies become more complex, the relationships between social entities become richly entangled and this significantly challenges our interpretative frameworks. Quantitative methods of all kinds have long been thought to be important tools in untangling these relationships.

Quantification is essential to archaeological inference and deals with numerical descriptions of empirical situations (Johnson 1978). Quantitative analysis involves the use of some method to manipulate numbers and measurements. Although critical theorists decry quantification as an inherently political act that strips the data of most of their meaning, it is difficult to see how comparative research of any kind could proceed without it.

The most basic form of quantification is counting, which implies that some sort of classification of the material recovered during the research process has been developed. Comparing counts and proportions of materials across stratigraphic

levels, contexts, and sites is compatible with every theoretical orientation, except those that take a radically critical perspective.

Measurement is related to quantification and is the assignment of numbers to an object or process according to some rule that is in common agreement among the scholars in the field. The units of measurement are not important as long as there is agreement on the measures and, importantly, on the procedures by which the measurements are obtained. Simple examples are taking the physical dimensions an object in inches, centimeters, or rods, or assessing the chemical composition of a ceramic vessel by parts per million. Measurement is important because it gives us access to mathematics, which offers a rich body of methods ranging from arithmetic to the calculus and beyond. Mathematics provides the tools by which more complex forms of quantitative inference can be employed to model and interpret the past.

Obviously, measurements must be meaningful—that is, they must bear some reasonably sound relation to the phenomena being described or modeled. Meaning is derived from previous experience or theory, and these provide guidance on the selection of things or attributes to be counted and quantities to be measured, and on the complex interrelationships between variables thought to be important to the process under assessment. Good measures may lead to more productive insights or more successful models, but it is often the case that what is chosen to be measured is selected on an ad hoc basis, just because it is possible, and not necessarily because it is carefully linked to the phenomena under analysis.

The definition of a robust quantitative idiom is perhaps the most critical aspect of how one reasons about anthropological or archaeological phenomena with numbers, statistics, or mathematics. A quantitative idiom is more than simply plugging numbers into a statistical formula or solving a series of differential equations; it is instead a recognition that *thinking* about some phenomenon using numbers is likely to

be productive (Aldenderfer 1987). Dwight Read (1987) offers a useful way of assessing the degree to which any quantitative idiom is robust. He describes well-defined (WD) or poorly defined (NWD) populations, and well-defined (WD) and poorly defined (NWD) variables. A WD population is one in which variability can be attributed to a known or knowable source or process. NWD populations, then, are those in which there may be multiple, and often unknown, causative agents that create variability. Many of the datasets archaeologists work with are samples of objects or processes from very large populations. Taphonomic factors transform these datasets in unpredictable ways, and low-level behaviors of discard and disposal often obscure evidence of the higher-level social activities. Although attention to middle-range theory may identify factors that have transformed our populations, it is rarely the case these factors can be fully eliminated. Better attention to sampling may help to create more WD populations, but limitations on time and resources tend to work against this.

A WD variable is one that, through prior experience or through a body of theory, has proved useful in previous analyses. In some circumstances, a hypothesized variable may be at least initially considered to be WD, until it is shown through analysis not to be. Some sub-fields in archaeology, including archaeometry (especially compositional studies of ceramics or metals), and archaeozoology (with standardized methods for counting, such as minimum number of individuals [MNI] and number of identified specimens [NISP]), have developed robust WD variables. When combined with observations from ethnoarchaeology, middle-range theory, or findings from other disciplines that pertain to the research problem, our variables tend to be far more WD than our populations.

But it remains the case that few archaeological questions combine WD populations with WD variables, and this makes the use of more advanced quantitative methods problematic in many research contexts. During the heady days of the “new archaeology,” we borrowed methods from many disciplines and applied them with gusto to our research questions. Although these analyses were exciting, most of them were framed in poorly designed (or nonexistent) quantitative

idioms; in consequence we either misused the methods employed or came up with spurious or unlikely results. And, while similar abuses of methods can still be found in the literature, the discipline has become far more careful and explicit in the definition of quantitative idioms and in how these are created to explore social life in the past.

Statistics, mathematics, and disentangling social life

Statistics is a branch of mathematical reasoning that deals with the logic of inference under conditions of variability, uncertainty, and error. Classical frequentist statistical inference, that is, the approach to statistical analysis developed in the twentieth century by Sir Ronald Fisher, Karl Pearson, and many others, takes the form of testing hypotheses that are framed in statistical terms. A relationship between two (or more) variables is proposed, a test is performed, and the result is compared to the null hypothesis of no relationship between the variables. Here the *statistical* significance of a result is evaluated, but not its *importance* to a larger research question. If one rejects the null hypothesis of no relationship, this does not imply that the result is *scientifically* valid, since it is very likely that many competing hypotheses could be invoked to explain the lack of relationship between the variables. This does not mean that the statistical relationship of variables should not be tested, but rather that everything depends on how the research question is framed, on how the tests are employed, and, most importantly, on conducting the research within a robust quantitative idiom.

A recent paper by Kohler et al. (2017) is a good example of how statistics, mathematical models, and a well-conceived quantitative idiom was used to explore post-Neolithic wealth disparities between Eurasia, North America, and Mesoamerica. In the absence of written records, mortuary analysis, especially the counting of and comparison between objects placed in tombs or graves, has been a common approach employed by archaeologists to assess wealth in the past. Wealth, of course, is one way to determine relative status within a society, and status differences

are usually read as likely indicators of the presence of social hierarchies. Typically, multivariate statistical methods such as cluster analysis have been used to search for patterns in the content of tombs; and, on the basis of the outputs, hierarchies (or their absence) were then inferred. This approach suffers from numerous problems, both statistical and anthropological. Because there are few formal methods by which the results of a pattern-search method can be assessed, they were often subject to confirmation bias. And, from a behavioral perspective, it is not always clear that the materials that accompany the dead are necessarily direct indicators of their social status.

To overcome these problems, Kohler et al. (2017) built a robust quantitative idiom around the anthropologically sound concept of intergenerational wealth transfers and how that wealth is reflected in the household. They propose that hunting and gathering societies should have relatively little material wealth to transfer to the next generation, while societies based upon either horticulture or fully domesticated plants and animals have more material wealth than can be transmitted. To avoid problems with disposal behaviors and artifact preservation across these regions and to create a usable “object” that could compare ancient and contemporary households, through the use of ethnographic evidence and modern surveys, they created a proxy measure of household wealth: house size.

To compare households with this proxy measure, Kohler et al. (2017) used the Gini coefficient, a mathematical formula that measures income or wealth disparities and is extensively employed by economists to compare and contrast wealth disparities between nations. The value of the coefficient ranges between 0 and 1; values of 0 reflect perfect wealth equality, while values of 1 indicate maximal inequality. As expected, median values of the Gini coefficient tracked model predictions: hunters and gatherers, 0.17; horticulturalists, 0.27; agriculturalists, 0.35. What was not expected, however, was that post-Neolithic coefficients in the Old World tended to exceed those in the New World. To explain this difference, the authors turned to a series of statistical hypothesis tests of political scale (here identified as ranging from the family to the state) and of hemisphere in the sample used to calculate the Gini coefficients. They also tested political strategy against

hemisphere, and neither exhibited a statistically significant relationship. What does appear to be the causal variable in the hemispheric difference in wealth inequality is an “agricultural extensification,” as the authors called it, which was made possible in the Old World through the presence of domesticated draft animals that could be used for traction, secondary products, or consumption. Such species are not present in pre-contact New World sites. In effect, these animals created a basis for a dramatic increase in wealth for those who possessed them, and thus led to larger intergenerational transfers of that wealth. These patterns were revealed by a nonlinear regression of calendar years as measured by radiocarbon samples, tree-ring dates, or actual calendar dates (using the Gini coefficient). Displayed on the regression plot was the estimated date of the appearance of domesticated plants.

Although some may choose to question the ways in which houses were defined and sites selected for inclusion in the study and to debate the criteria used for defining political entities, the strength of this study resides in the careful integration of appropriate statistics, a well-understood mathematical model, and a robust quantitative idiom informed by anthropological theory. Using these tools, the authors have created an exemplary analysis of social life in the past.

Archaeological studies that employ models from human behavioral ecology (HBE) are excellent examples of the combined use of quantification and mathematics. Zeanah (2004), using a central place foraging (CPF) model, examined the sexual division of labor in the Late Holocene and in ethnohistoric periods among hunting and gathering societies in the Carson Desert of Nevada. Previous studies of these groups suggested a subsistence shift from a mobile, hunting-oriented strategy to a semisedentary gathering strategy, in response to diminishing densities of game. But, instead of looking at men’s and women’s activities jointly, as a means by which to predict site placement on the landscape, he contrasted women’s foraging goals with men’s hunting goals within a CPF model, in order to determine which (if either) was the optimal strategy.

Human behavioral ecology offers a number of distinct advantages for building a robust quantitative idiom. Its origins are in microeconomics,

it was subsequently translated into ecological science, and its advocates have developed a wide range of mathematical models that have utility in the analysis of making decisions about subsistence activities. Typically, HBE models have the following components: a goal (risk avoidance, maximization of energy return), a decision strategy (take a resource upon encounter or wait to explore a new patch), trade-offs (circumstances in which an alternative strategy might be more effective), recognition of constraints (what technologies are available), and, finally, a currency (a measure of costs of procurement, or time spent in a task). Quantification involves using the selected currency to calculate travel costs, the processing or handling times of specific resources, and search costs and to make estimates of the productivity of different resource choices—usually the caloric content of the species that could be exploited. The equations of the model are then employed to calculate, for example, return rates, which are used to infer an optimal diet within the context of the given constraints and goals. Zeanah's innovation here lies in examining women's and men's subsistence choices separately, which allows him to look at site-placement choices in a detailed manner and to suggest that, in this case, women's and human subsistence choices were not complementary but actually conflicting. This in turn suggests that the analysis of subsistence shifts in ancient settings needs to take the division of labor into account more seriously.

There are, of course, numerous objections to the application of HBE models to explore the social lives of past peoples. HBE models are based upon assumptions that are usually difficult or impossible to control. The environmental reconstructions upon which these models are based are often very coarse, and thus cost estimates may well be incorrect by orders of magnitude. Advocates of feminist perspectives on the past argue that defining the sexual division of labor in narrow terms promotes stereotypical thinking about women's lives. Although all of these problems are real, such critiques ignore the benefits of thinking about the past in quantitative or mathematical terms. Models have different utilities: some are conceptual, and their construction may promote clearer thinking about a process; some models are built to make specific predictions about a process, and others are built to explore a process

under different scenarios. These are significant advantages, and they provide an important alternative to the simple interpretive narratives of the past.

Multiscalar approaches to social life in the past

Archaeologists, following the lead of human geographers, have long been aware that social activities take place at multiple spatial levels within a society. Quantitative methods of all kinds—central place theory, distance-decay models, locational analysis, and many others—have been employed to define settlement hierarchies, trade relationships, activities within sites, and other social processes. The geographic information system (GIS) has become a standard analytic tool in the field, and spatial statistics of all kinds are embedded in the major software suites. R programming language, as well as Python and others, has been increasingly employed to look at spatial patterns in the archaeological record.

A common critique of these methods is that they define patterns without necessarily identifying causal factors that have led to their creation. Some theoretical perspectives, like entanglement theory, believe that relatively simple quantitative models of social and spatial processes are of little utility and are unable to capture complex anthropological processes. Even advocates of quantitative methods have expressed concern that these models have not lived up to their potential. A more likely explanation for the dissatisfaction with many of these models is that they were not created within a robust quantitative idiom.

Over the past decade, new quantitative and mathematical models have been developed to look at multiscale social phenomena of the past. One of the interesting outcomes of Kohler et al.'s (2017, 621) model of intergenerational wealth transfer was the observation that "wealth differentials are more strongly associated with increasing settlement size, regional population size and regional population density in the Old World than in the New World." They speculate that these scaling differences between the Old and the New World are based upon a more

intensive focus on economic specialization and long-distance trade in the former. The growth of cities and the attendant settlement hierarchies can be added as a possible causal factor. But a recent model developed by Haas et al. (2015) challenges the role these factors play in creating settlement hierarchies.

The settlement hierarchies of complex societies are described as “heavy-tailed,” which means that these societies are characterized by a large number of very small settlements and very few very large ones. This distribution can be formalized mathematically using a power-law function. This pattern is postulated to be driven by agriculture, warfare, and economic specialization, which lead to the development of central places. Haas et al. (2015) tested these assumptions using the settlement patterns of eight New World hunter-gathering populations in varied environmental contexts, and discovered that each of these settlement patterns is also heavy-tailed and could be described effectively by the power-law function. This surprising result indicates that incipient forms of settlement hierarchy could develop in mobile hunting and gathering societies and thus do not require more complex social formations for their development. Although a more complete explanation of the social processes that could account for this finding remains to be articulated, the authors suggest that “preferential attachment to previously occupied locations” may be operative (Haas et al. 2015, 15–9).

The quantitative idiom for this analysis is built around two variables that are reasonably well defined and have some ethnographic warrant: counts of diagnostic projectile points; and site area. The former signals person-hours of occupation, which means that lengthier occupations should result in the deposition of more points. Using temporal diagnostic points reduces the possible confounding effect of other uses of the site by groups using that space in different temporal periods. Site area reflects the size of the coresident group; larger groups tend to require more horizontal space. Should hunter-gatherer settlement systems follow the power-law model, we would expect both point-count and site-size estimates to reflect a power-law distribution.

These variables are not perfect measures of the size of the coresident group or of the dimensions of the site. The numbers of points at a site may

be underestimated by the combined effects of looting and taphonomic factors. Differences in surface collection strategies and the techniques used to define site area may also be problematic. Despite these potential sources of error, Haas et al. (2015, 7) argue that linear sources of error such as these would have little effect on the data and that, taken together, these error sources are well known to generate log-normal as opposed to power-law variation.

Social network analysis (SNA) has emerged as a powerful tool for exploring multiscale social processes. The method has origins in multiple disciplines, and archaeology has borrowed liberally from most of them. Very simply, SNA is based upon nodes and the connections between them. Nodes are simply the entities within the model, and in archaeology these are typically sites. Connections describe how nodes are linked to one another. Analyses of networks focus either upon the position and connectivity of nodes or upon the structure of the entire network. The mathematical foundations of network analysis come from graph theory, and a rich body of metrics has been developed to describe network structure and node characteristics.

SNA is remarkably compatible with many theoretical orientations in archaeology and has been used to explore an amazing variety of research questions in a diversity of regions, for example the diffusion of innovations, the flow of goods, interactions between Maya polities of the Classic period, exchange systems in foraging societies, and site placement in the Mediterranean. One of the great benefits of SNA is that it can be applied at multiple spatial scales, from the local to the pan-regional. This flexibility implies that SNA can be embedded in robust quantitative idioms; but, as in any mathematical model, the outputs of SNA must be interpreted within the idiom. The model-neutral metrics are of considerable importance as interpretative aids. SNA models also lend themselves very well to computational modeling and to other forms of computer simulation.

Mills et al. (2013) is a good example of an SNA embedded within a compelling quantitative idiom. The period from 1200 to 1450 AD in the American southwest was characterized by migrations, regional abandonments, and the appearance of larger villages and nucleated settlements. As the authors note, these patterns

were observed primarily at the level of the site or small region, and then extrapolated through comparisons of material culture across regions. Combining SNA, GIS, and an impressive database of archaeological ceramics representing a very large portion of the western American southwest, the authors discovered dramatic changes in network structure over the 250-year period under study. These included the eventual creation of two more or less separate networks, one operating in the south and the other in the north. Over time, both networks shrank in spatial scale until they essentially disappeared by 1450.

The quantitative idiom employed in this study was based on networks of decorated ceramics. Mills et al. (2013, 5785) postulate that the decorated ceramics were used in a variety of social contexts and may have served as markers of ideology or group identity. The anthropological processes that are thought to lead to similarities in ceramic assemblages at different spatial scales include local transmission of production, population migration, and the creation or maintenance of social boundaries. Frequencies of different ceramic wares, then, were the proxy measure for these social relationships. While the SNA does not permit an exact definition of the social process responsible for a relationship between sites on the basis of this proxy, it did create a context for the exploration of hypotheses about migrations and population aggregation that could be tested with other archaeological data.

SEE ALSO: Computer Applications in Archaeology; Measurement Theory; Network Science; Statistics in Archaeology

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Realist Philosophies of Science

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Introduction

At its most general level, scientific realism is a view of the nature of reality and how that reality can be studied and understood. A basic assumption of the perspective is that there is a real world, both observable and unobservable, that different observers can independently experience through their naked eye, instrumentation, or theoretical modeling. The assumption of a completely objective reality is the underlying principle of science and is taken to explain the success of science. This entry reviews assumptions of scientific realism, challenges to it, and the status of scientific realism in the historical sciences.

Scientific realism: basic assumptions and their rationale

As a philosophy of science, scientific realism emerged in the middle of the twentieth century largely as a reaction to logical positivism, which encountered difficulties with its verification theory of meaning, analytic–synthetic distinction, distinction between observational and theoretical terms, and the theory ladenness of observation, among other problems (Liston 2017, 2–11; see **POSITIVISM**). Scientific realism became the leading philosophy of science following these debates.

Among the claims typical of scientific realism are the following, though not all scientific realists support all claims (Leplin 1984, 1–2):

- The best theories are at least partially true.
- The best theories do not employ central terms that are nonreferring expressions.

- To say that a theory is approximately true is sufficient explanation of the degree of its predictive success.
- The approximate truth of theory is the only explanation of its predictive success.
- Even if a theory employs expressions that do not have a reference, a scientific theory may be approximately true.
- Scientific theories are in a historical process of progress towards a true account of the physical world (so science makes progress).
- Scientific theories make genuine, existential claims.
- Theoretical claims of scientific theories should be read literally and are definitely either true or false.
- The degree of the predictive success of a theory is evidence of the referential success of its central terms.
- The goal of science is an account of the physical world that is literally true. Science has been successful because this is the goal that it has been making progress toward.

These claims have been grouped in scientific realism into three commitments. The semantic commitment supports the claim of a literal interpretation of scientific claims: Claims will be true or false depending on whether or not the entities in a theory exist and have been correctly described. The metaphysical commitment is a commitment to the claim that the mind-independent entities investigated by well-supported theories exist objectively. The epistemological commitment supports the claim that the entities in well-supported theories do exist. In review, the first and second commitments support claims that in a well-supported theory the entities in the theory do exist. The third commitment supports the notion that claims about the entities in a well-supported theory are true.

Arguments in favor of the claims of scientific realism have been advanced, often in reply to skeptical adversaries. Three are mentioned here.

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Predictive success

A widely accepted observation of modern science is that many scientific theories are highly successful in predicting and explaining multiple phenomena, often with an extraordinary degree of accuracy. If scientific theories were figments of scientists' imagination and not anchored in reality, how can their predictive success be accounted for other than the base assumptions of scientific realism or a miracle?

The miracle argument

An implication of the argument above is that scientific realism is the only philosophy of science that does not make the success of science a miracle.

The corroboration argument

If entities do not exist as described in the assumptions of scientific realism, then the fact that different investigators using different modes of detection are able to identify the same entity would be another miracle, another astonishing coincidence.

Challenges to scientific realism and responses to those challenges

There have been many vigorous arguments against the claims of scientific realism. Four of the more common arguments in the philosophy of science literature are reviewed here, with brief replies by scientific realists. Arguments against strict realism from the perspective of perception theory and consciousness studies are then introduced.

The pessimistic induction argument

A common antiscientific realism argument points to the eventual failure of theories that were once considered empirically successful. This is true as well for successful theories whose unobservable terms are no longer thought to be existent. The pessimistic conclusion is that even well-supported theories today are not true or even approximately true either, and support

for a theory from a wide variety of empirical evidence is no guarantee that a theory is true or approximately true. Realists have replied that since replacement of one theory by a better one is a feature of the progress of science, it is to be expected that aspects of earlier theories will fail. This just proves the claim of the progress of science. In some instances, a theory may fail, but a well-supported concept or two, such as the concept of an atom, may be incorporated into a different theory in some form.

The social constructivist argument

This argument points out that during periods of scientific revolution, rapid change occurs in scientific knowledge. If scientific knowledge progresses through time at a regular rate, how are we to account for these sudden changes? Some social constructivists argue as well that new theories may only be a response to the appearance of new paradigms, paradigms that are incommensurable with older ones. Realists reply that the majority of scientists do research without considering whether their research is an example of one philosophy of science or another. For example, during the development of quantum mechanics in the 1920s, logical positivism was the dominant philosophy of science.

The underdetermination of theory by observable data argument

In some cases, the same observable empirical evidence supports several rival theories, but their unobservable data differ. These differences provide a skeptical argument against the truth of any of the theories. Realists have countered this argument by accepting the idea of underdetermination, for in their view theories remain only approximately true regardless of what evidence emerges, at least at the present. Over time, theory testing will get to the truth of the matter.

Skepticism about inference to the best explanation

In their research, scientists judge rival theories in part by deciding which hypothesis or set of hypotheses provide a better explanation of the

evidence than their rivals. But how is “better” determined? During times of scientific revolution and the emergence of new paradigms, what is considered “better” may shift. Scientific realists have replied that shared criteria like simplicity, consistency with other theories, and scope provide objective standards that aid this decision process. Scientific realists reply again that this is just part of the process of working toward a true theory.

A challenge to scientific realism not highlighted in the philosophy of science literature is our ability to sense correctly the world as it is. It seems there are physical limitations to how we access the world both in our sense organs and in our consciousness. Realists and people in general tend to take for granted the following five assumptions about our perception of reality: We are in immediate and direct contact with the world “out there” through our five senses; our information about the world is incredibly detailed and rich in information; we are capable of absorbing enormous amounts of information about the world quickly if not immediately through our senses; we all experience the same world; and the world exists “out there” independent of us. Perception theorists have challenged all of these assumptions (Epworth 2014). For example, the eye as one of these sense organs has structural limitations and other characteristics that limit and influence what we see and how we see it.

Likewise, our consciousness is not what we think it is. Among the conclusions neuroscientist Bruce Hood (2012) reached in his research are: “our brains use illusions to recreate the world. Everything is processed and abstract, with the brain putting in a large amount of effort to organize, interpret, and fill in missing information based on past experience,” and “our brain constructs models of the external world that provide a coherent story [of a complex reality] that enables us to interpret and predict what we should do next.”

Although we may use illusions to recreate the world, this is not always successful. Try eating rocks to save money on food, for example! According to Jaccard and Jacoby (2010, 7–10), “the obdurate character of our social and physical environment” will be a deciding factor in separating out useful and harmful interpretations of reality. In this view, scientific realism is about

the obdurate character of our social and physical environment.

There are also a variety of forms of what are called antirealism that provide alternative philosophies of science to that of scientific realism. Examples are empiricism, historicism, some feminist approaches, and various forms of pragmatism (Chakravartty 2007, 16–26).

Scientific realism in the historical sciences

While scientific realists are willing to accept the existence of observable and unobservable entities in physical sciences like experimental physics and chemistry, they generally deny that such realities exist in the social sciences and ignore historical sciences like paleobiology, paleontology, and archaeology. Because of this omission, the realism debate has been skewed in several ways (Turner 2007). By concentrating on experimental realism, the debate has favored emphasis on unobservables in experimental physics rather than in prehistory, deemphasized local underdetermination problems, which are more common in historical than in experimental sciences, emphasized novel predictive successes, which are rarer in the historical sciences, and ignored differences in the kinds of unobservables in these two different kinds of disciplines. All of this is likely another sign that historical sciences like archaeology are considered somehow less scientific than experimental physics or chemistry. Nonetheless, a mature, balanced overview of scientific realism will have to accommodate the gamut of the sciences, not just a select, favored few.

SEE ALSO: Empiricism; Philosophy of Science; Positivism; Scientific Revolutions

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Science and Feminism

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Feminist archaeology has overturned how archaeologists think about and interpret sex and gender in the past and made a strong contribution to challenging the artificial division and opposition of “nature” and “culture.” It therefore has had a significant impact on how science is theorized in archaeology. The impact of feminism was felt later in archaeology than in cognate disciplines, or the philosophy of science, only gaining substantial mainstream attention by the late 1980s. At this time, two important appraisals were made of the subject’s androcentrism. The first critique demonstrated failings in how archaeology had written, or rather *not* written, about women in the past. Women had largely been ignored, casted as lacking agency, or past gender relations received little interrogation, ultimately reproducing and naturalizing modern experiences of female roles and status (Gero and Conkey 1991). The second critique focused on the role of women in the practice of archaeology, pointing to the restricted range and forms of work women were engaged in, and how this led to their marginalization in the political hierarchies and strategic positions in the work environment (Wylie 1997). Inspired by feminist theory, many archaeologists took on the “double challenge,” noted by Gero and Conkey (1991, 6), to both capture gender in the past and rethink conceptions of relations between women and men, producing a rich tradition of gender research in archaeology.

Archaeological sciences were not exempt from this movement. In a now classic example, Hastorf (1991) investigated paleobotanical remains and stable isotopes from human skeletons in combination with spatial analysis and ethnographic sources, to reexamine gendered food production and diet over the period during which Inca political influence was established in the Andes. The results demonstrated that men’s consumption

of maize increased more than women’s after the Inca conquest. Hastorf (1991) argued this was due to men’s greater involvement in feasts held by the Inca, as they sought to incorporate wider territories in their new political organizations by drawing on existing gift exchange practices. The study did much to demonstrate the importance of gender and household studies to answering questions about macrohistorical processes such as state-formation, but also emphasized the many ways in which social and cultural dynamics such as changing gender relations can intersect with research areas such as food production.

The feminist critique found a footing in archaeology in parallel to an important paradigm shift in Anglo-American archaeology. From the 1960s, “new archaeology” had sought to position archaeology as a scientific discipline, engaged in the task of determining and developing appropriate methodologies to test and produce laws of history, akin to those of the natural sciences. From the 1980s, postprocessual archaeology derived from postmodern thought sought to demonstrate that subjective social and political assumptions do influence the interpretation of archaeology: that data could not be understood as free from the cultural context in which the work was produced and written (Jones 2002). Debates between archaeologists advocating one of these positions could be vitriolic at times, but the issues raised by these contrasting approaches, that of the nature, extent, and possibilities of objectivity in research, had already been negotiated for some time by the philosophy of science and the feminist critique of science.

Feminists’ perspectives on objectivity in science have been characterized as highly polarized, stretching from arguing that it is only through the objective use of empirical data that value-free conclusions can really challenge the gender biases prevalent in society, to extreme relativism, in which science is thought to be so permeated by androcentrism, its knowledge should be entirely rejected (Wylie 1997). Wylie (1997) has argued that feminism’s commitment to making a real difference encourages researchers away from

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supporting all-encompassing objectivism and extreme relativism, and, for the most part, feminist writing on scientific objectivity is notable for its call to find a pathway through both method and interpretation from multiple viewpoints, exposing the places where data and results are compromised by bias or culturally specific social values. By constantly assessing how scientific knowledge is being produced, who for, and the values by which it is judged as meaningful, feminism has sought to find space for different voices in science. For example, feminist scholar of science studies Donna Haraway (1988) has promoted a feminist version of objectivity, which she calls *situated knowledges* (what Wylie (1997) calls the view from “somewhere”), arguing that to do feminist science effectively, the practitioner must explicitly position themselves with respect to political and social debates of the contemporary world. Overwhelmingly, in among the variety of approaches, this has been the message from feminist philosophers of science; that knowledge is always contested and partial, that systemic bias is capable of permeating the questions science asks, its methodologies, and empirical results, but that this situation can be effectively challenged from a plurality of perspectives to promote what are ultimately more rigorous and productive understandings of the (contemporary) world.

Writing in 1997, Conkey and Gero summarized what they saw as the four significant points archaeology had adopted from feminist philosophy of science. (1) The role political contexts continue to have in defining who produces knowledge and the way it is assessed is undeniable. For example, the concepts such as “man the hunter” and “women the gatherer” have been repeatedly shown to be based on lazy stereotyping, but continually to be frequently reproduced both in text and visualizations of prehistory. (2) True objectivity is unachievable, and claims that conclusions are based on it are likely to be unreliable. Multiple routes to historical insight are now taken, with the confident use of fiction and discussion of emotion to expand the repertoire of archaeological inferences. (3) Challenging binary thinking and taking ambiguity in data as meaningful has often been achieved through “intimate knowledge,” such as that of Spector’s (1993) account of life at a Wahpeton Dakota

village, starting from close description of an awl as entry point into exploring daily life and gender roles. (4) There is a commitment to challenging the current conventions, by increasing the variety of voices heard in archaeology.

From the late 1990s, third-wave feminism shifted the lens from gender *sensu stricto* to constructions of identity and the body more broadly, analyzing the intersections between age, gender, sex, class, sexuality, kinship, and ethnicity. A pioneering example of this approach can be seen in Meskell’s (1999) investigation of ancient Egyptian social life at the Deir el Medina cemetery, illustrating the participation of material culture in the performance and negotiation of Egyptian attitudes to corporeality and personhood, mediated through different aspects of identity such as age and status. The archaeological sciences have made a strong contribution to identity studies, often through techniques focused on the human skeleton (such as isotope studies on diet and mobility) and paleopathology and osteological techniques on disease and habitual activity (see OSTEOLOGY and PALEOPATHOLOGY), particularly in illustrating the variation across populations and recovering the history of those who may be materially less visible in the archaeological record (i.e., buried without grave goods). This analysis can be presented with little explicit reference to feminism, signaling perhaps that many of the key points stressed by feminist archaeologists have by now been adopted by the discipline.

Such optimism is not shared by everyone, as evidenced in the 2013 special addition of the journal *Current Swedish Archaeology* on archaeological science in archaeology. Papers in the volume repeatedly highlight tendencies in the interpretation of data produced by the natural sciences toward essentialization (e.g., the categories of male and female are defined by unchanging characteristics), especially when social identity is inferred directly from biological markers. In this respect, the use of DNA and ancient DNA (see GENETICS: ANCIENT) to answer questions of population spread, migration, and origins has been particularly controversial. The ability of genetics to reveal biological sex and genealogy will undoubtedly contribute hugely to the future of archaeology, but how historical significance is understood from the data requires both the critical appraisal of how the

data informs on specific archaeological questions and subsequent reevaluation of existing models or hypotheses. As Wylie (1997) argues, despite extensive debates about archaeological method, the means by which conclusions are drawn in archaeology is often by moving repeatedly between background knowledge and theories, and the evidence, to create chains of inference. Irrespective of where individuals stand on both science in archaeology and feminist approaches, this now characterizes archaeological method, with researchers pursuing a variety of perspectives in relation to objectivity versus social constructivism.

Despite the substantial literature reflecting on and championing the feminist perspective on science outside the discipline, and separately receiving discussion and making undeniable contributions to the development of archaeology, explicit considerations of the impact of feminism on *archaeological science* have faded since the first rush of papers in the 1980s and 1990s. Although ideas from key feminist thinkers such as Haraway (1988) and Wylie (1997) have been drawn upon (e.g., Jones 2002), claims to an explicit feminist standpoint in the archaeological sciences more recently have been minimal. While the varied feminist critiques have largely focused on the archaeological discipline as a whole, multiple positions are taken up by archaeologists with respect to science, ranging from the unambiguous classification of archaeology as a natural science, to suspicion, and this appears to have resulted in feminist perspectives being lost in among debates about the relationship between archaeological theory and archaeological science.

This does not mean, however, that recent developments in feminist theory more broadly have not been felt in archaeological practice. The “material turn” in archaeology, and the humanities more widely (see SUBSTANCES AND MATERIALS), has involved a critique of anthropocentrism often drawing on the feminist skepticism that a universal “human” perspective can be carved out separately from the material, animal, and ecological world (Fredengren 2013). Under various guises, such as symmetrical archaeology (see SYMMETRICAL ARCHAEOLOGY), these approaches have argued that the division between “objective” science and “constructivist” humanities was another example of the kinds of binary thought

feminism had criticized. Rather, ontological accounts are now increasingly favored, focusing on what the world “is,” in place of the previous debates between processual and postprocessual archaeologies about how best to “know” the world. The first steps towards archaeologies inspired by this approach have largely focused on “things” and materials, and tend to favor drawing on a wide variety of data, including that of archaeological science. For example, Fredengren (2013) discussed how past bodies can be investigated as assemblages drawing on data from isotopes and DNA, pointing to how recent DNA analysis of dental calculus reveals changing assemblages of humans and bacteria over shifts in diet. Future research will no doubt bring more examples in this vein.

Within archaeology, the concepts of “science” and “feminism” are at once both sets of analytical practices and critiques on the discipline itself. Many of the conflicts and objections around both the use of science and the feminist perspective in archaeology have arisen when these concepts have been considered as mutually exclusive products of archaeological research. Recently, it has been recognized that they are, rather, practices that better inform research, and as such these concepts have been used to find more fertile ground for interrogating the past, and become more readily combined.

SEE ALSO: Gender and Sexuality; History and Sociology of Science; Science and Politics; Scientific Practice

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Science and Politics

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“Science,” in common understanding, is defined thus: “knowledge or a system of knowledge covering general truths or the operation of general laws especially as obtained and tested through scientific method” (Merriam-Webster dictionary: <https://www.merriam-webster.com/dictionary/science>), with the scientific method defined thus: “principles and procedures for the systematic pursuit of knowledge involving the recognition and formulation of a problem, the collection of data through observation and experiment, and the formulation and testing of hypotheses” (Merriam-Webster dictionary: <https://www.merriam-webster.com/dictionary/scientific%20method>). Truth is commonly identified as the observable state of occurrence of *things* (that constitute the world) that are recognized as they are by everyone, anywhere, at any time. When it comes to *material things*, their state of being can be observed, described, and shared, so long as a certain rule or framework is established and adopted, and a certain equipment is deployed. Exposing a material thing to a certain condition transforms it from a certain state to another in a certain manner, regardless of who does it, when it is done, and where it is done. In other words, secure forms of *causality* and *repeatability* exist, which can be established if we *systematically* handle material things by formulating hypotheses and testing them through observation and experimentation. *Indeterminacy* in the specification of causality cannot ultimately be overcome because of the inevitable intervention of the mechanical–technological limit of resolution and of observation; and the philosophy of science dedicates considerable effort to solving various issues concerning how to deal with indeterminacy, how to secure repeatability, and to what extent this can be achieved. When it comes to dealing with *human beings*, also things

constituting the world and an important subject of scientific endeavor, however, we must confront a fundamentally different set of issues; for the consideration of issues concerning science and politics, we must deal with human beings as a subject of science, as the practitioner of science, and as the recipient of the outcomes of scientific endeavor.

Material beings have neither consciousness nor memory, and do not change their behavior individually or collectively in reaction to changes to their environment/effects from the outside. Human beings have consciousness, memory, and language, and other means to communicate their thoughts; they change their behavior individually and collectively in reaction to changes to their environment and to effects from the outside. They also have the ability to choose not to react to them. The fundamental and constitutive characteristics of the former are the foundation of the repeatability of cause–effect relationships. That of the latter, however, mean that cause–effect relationships are not always repeatable, in that human beings might change the way they react to a certain condition by referring to what happened previously under similar circumstances. They can also change the way they react to a certain condition by referring to what they know happened elsewhere under comparable circumstances. Most often, the society of which a person has acquired knowledge is their own one; this being the case, they can change the way that they act by referring to what they have learned, and such change effectively changes the society of which s/he is a member.

This endless feedback loop, conceptualized by Anthony Giddens as the double hermeneutical nature of social sciences (Giddens 1984, 284), is exactly the point where science has intrinsic and inevitable linkage with politics. The methods of science constitute sets of tools, skills, logics, and ways of thought, and attitudes as well as subject matters; each of them forms a unique mode of existence which can be characterized as a “habitus” (Bourdieu 1990). A habitus, or an embodied way of how to get on

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with the object and subject world, consists of a certain set of knowledges and values; these are internalized through the recursive enactment of a certain set of practices on, by using, and mediated by a certain set of items/resources, material, virtual, symbolic, or otherwise. Such a set reflects/is constituted by the mode in which those items/resources are distributed across the social landscape in which scientific practices are embedded and conducted, and such items/resources are *unevenly distributed*. Negotiations over the ways in which different resources are allocated to different social groups take place all the time at each and every social context, including laboratories, research facilities, and excavations. If we categorize such negotiations as political practices, virtually every moment of our daily lives, including our scientific practices, is political. Furthermore, the uneven distribution of various types of resources and capitals, including both economic and cultural-symbolic, is engineered by those who are dominant in each unit of social integration, ranging from such microunits as a laboratory and an excavation through a globalized sociopolitical/economic sphere, and resistances are organized by the subordinate. Scientific revolutions, conceptualized by Thomas Kuhn as “paradigm shifts” (Kuhn 1962), are caused by not only the accumulation of knowledge, inventions, and technological developments but also those human factors involving the reproduction and transformation of power relations, which can only be characterized as political.

This can be seen most characteristically in the context of colonial archaeological practices. Against the background of the “diffusionist” paradigm—which explains sociocultural changes as the result of migrations and/or the spread of sociocultural traits—complex societies with variously developed social hierarchies in colonized areas, most prominently exemplified in the famous case of the site of Great Zimbabwe, were interpreted as having been constructed by migrant populations originally from the core regions of the pristine ancient civilizations or their vicinity. The achievements of these civilizations are acknowledged, since modern European societies are identified as their inheritors. Various kinds of pseudoscientific practices, including intentionally arbitrary

readings of ancient literature/chronicles and, again, intentionally arbitrary comparisons of specific attributes of indigenous artifacts with those of the aforementioned “civilized” areas, serve to demonstrate the existence of direct connections that resulted from migrations from the pristine ancient civilization areas and their vicinities to the colonies.

The “diffusionist” paradigm itself was organically embedded in the socio-political/cultural/economic conditions of the nineteenth and early twentieth centuries, when competition between the nation states of Europe and elsewhere over territories, resources, and markets generated the condition in which the allocation of aforementioned resources was engineered by the state authorities for political purposes; this included the tight integration of the inhabitants of a state as a distinct ethno-national group with a shared history (of enduring hardship) and destiny. The newly developed middle class/educated elite, including practitioners of newly disciplined scientific disciplines, played a fundamental role in the (re-)invention of ethno-national traditions, and when it comes to colonial interventions, the outcomes of their scientific endeavor legitimized colonizations as enlightening endeavors. It has to be noted that the sense of legitimacy and duty driving the elite at the time was significantly based upon belief in the absolute supremacy of empirical sciences over folk/indigenous knowledges; the political habitus, so to speak, based upon this empirical science-based habitus, made the aforementioned pseudo-scientific practices legitimate and natural, despite that the latter fundamentally betrayed the principles of empirical science.

Let us continue tracing the historical transformation of the relationship between archaeological practices and contemporary society. By dismissing the “diffusionist” paradigm as the “aquatic view of culture” (Binford 1965, 204), the so-called processual paradigm emerged in the 1960s. This paradigm was based upon the belief that archaeological knowledge production was a scientific endeavor in the sense that the traces of human thoughts and deeds could be treated in the same manner as material things. Alternatively, some would claim that the “paradigm” tried, and still is trying, to limit its scope to the elements of human thoughts and deeds that showed

material thing-like patterns. In this framework, the archaeologically retrievable traces of human thoughts and deeds were examined in terms of their co-variation with traces of the factors that could be inferred to constitute the *environment* of such thoughts and deeds, and their *transformation* was explained in *functionalistic* terms—that is, the transformation of patterned thoughts and deeds for the regaining of the stability of the social whole. It was intended to minimize any involvement of subjectivity, a theoretical premise directed by logical positivist versions of the philosophy of science (see POSITIVISM), as well as Karl Popper's injunction to secure the falsifiability of statements (see EMPIRICISM). This reliance upon positivist philosophy exemplifies the habitus shared by many sectors of archaeological communities across the developed world at the time, which was organically connected to the sociopolitical climate of the era. This was the Cold War equilibrium based upon the balance of military power between the United States, the USSR, and their respective allies, which made social phenomena the subject of engineering based upon functionalist input-output modeling. Moreover, input-output modeling-based research projects were directed toward the generation of clear and coherent results, which proved successful in attracting research funding. Furthermore, the Cold War equilibrium prevented rising colonial and post-colonial tensions from surfacing to cause significant impacts upon the policy frameworks of the United States, the USSR, and their allied nations, particularly if they might jeopardize the implementation of the policies concerned. Those conditions enabled the dominant habitus embedded in the archaeological practice of the time to identify and constitute archaeology as a search for law-like generalizations, a discipline modeled on the natural sciences.

The end of the Cold War (in the form of the collapse of the USSR and its allied sociopolitical, economic, and cultural block) in the early 1990s accelerated the process in which first economic, and then sociocultural and political globalization led to the deepening of post-colonial tensions, and their surfacing to the extent that they began to have significant impacts upon international politics, which had begun well before the end of the Cold War. This, together with

other consequences of globalization, prominently including the re-perpetuation of center and periphery relation-based asymmetry in access to capital and resources, has led to the rise of the fundamental critique of modern science as a habitus perpetuating the western domination over their former colonies by prioritizing the Cartesian view/model of the order of the world. At the same time, the rise of the *internal critique* of the scientific community has led to the increasing realization of *indeterminacy* in scientific knowledge production and *causation*. Those trends have come together and resulted in the opening up of the critical discursive space of the history and philosophy of science in which the involvement of *historical contingency* and indeterminacy in scientific knowledge production is linked to the relation of dominance that exists between the producer and consumer, between the imposer and the recipient, and between the observer and the observed among those who are involved and/or implicated in scientific knowledge production.

In archaeology, this realization initially took the form of the emergence of so-called post-processual archaeologies, which emphasized the value-ladenness of archaeological knowledge production, the importance of promoting multivocality within it, and the intrinsic and inevitable linkage between politics and archaeological knowledge production. In the early phase of the postprocessual "movement," the relationship between those who advocated the search for law-like generalities in the traces of past human lives as well as past human lives themselves and those who emphasize historical contingency in the patterning of human practices and the importance of the conscious, strategic use of material culture was a hostile one. However, it is presently increasingly common to combine these views and approaches by selectively adopting their theoretical and methodological components in individual research paradigms and projects. This not only shows the maturity of archaeology, which some would describe as the emergence of multiple "archaeologies," but also is a reaction to an increasingly complex world containing increasingly polarized value systems and world views. Such a condition requires a highly nuanced treatment of the subject of one's research and a highly strategic choice of subject

matter, and of the manner of presenting the outcome.

It has to be noted that presently a new and somewhat problematic trend is emerging: The rapidly increasing popularity of the application of natural scientific tools such as strontium and other isotope analyses and ancient DNA analyses is resulting in an uncritical readoption of diffusionist modes of explanation for social transformations, and the restriction of the subject matter of archaeological investigation to what can be simulated in the form of cause–effect linkages. This trend can be seen as a way of reacting to the increasing complexity of the world and the polarization of values and world views by confining one’s research interests to what can be simply and (apparently) comprehensively described and/or explained. The development and elaboration of tools and means with which to pinpoint the place of origin of an archaeological material, whether it be an artifact or a skeletal individual, are undoubtedly of value. However, if they unwittingly encourage an attitude of uncritically connecting the outcome of such application of natural scientific tools to archaeological inferences generated by archaeological paradigms that have long been rejected owing to their harmful political implications (such as discrimination or the dismissal of indigenous world views fostered by colonialism), we will need to adopt a cautious and critical approach to them.

In conclusion, it needs be emphasized that all scientific practices embody political elements in their performance as much as their outcomes, and that any scientific practice that concerns itself with human thoughts and deeds is inseparable from relations of dominance. In order to practice archaeology (or archaeologies)

in a socially responsible manner, we have to fully understand the enabling, constraining, and risk-generating elements and characteristics of science, as well as to recognize exactly in which domains we can seek law-like generalities and in which we have to be aware of, and focus on, historical contingencies and indeterminacy. All those points can only be fully appreciated if we accept the fact that the conduct of science is a political act.

SEE ALSO: Experts and Stakeholders; Public Archaeology

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Scientific Practice

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Introduction

The concept of “scientific practice” in relation to archaeology has varied both geographically and temporally. Even today, varying opinions exist as to what this term actually encompasses. Some will see all of archaeology as “scientific practice,” with trenches, surveys, and typological study of past material culture being “experiments” and yielding new facts and information. To others, “scientific practice” has little role in a humanities subject that studies multiple “truths” and has few means of empirically validating theories. However, perhaps the most common current understanding of “scientific practice,” given the huge diversity of biomolecular, archaeometric, and chronological methodologies that are now available to archaeologists, frames archaeological science as a subdiscipline, and just one part of an approach to the study of the past. In line with this, here we take “scientific practice” to mean the application of laboratory-based scientific methods, often imported and adapted from diverse fields in the natural sciences, in order to produce empirical data that can be used to test well-formulated questions.

Yet while this definition may suggest a simple categorization of “scientific practice” within archaeology, we note that this is misleading. Latour (1987, 1993), among others, has argued that all science is inseparable from its social, political, and economic context, and this is particularly true for archaeological science. “Scientific practice” in archaeology involves collaborative negotiation between curators, excavators, numerous different scientific specialists, governments, landowners, and, in a “world archaeology,” diverse national archaeologies,

Indigenous groups, and other stakeholders. Moreover, archaeological science is accountable to the public tax-payer, policy-makers, and politicians (often across national boundaries), and funding bodies operating on increasingly constrained budgets. In this entry, we address the issues arising from these diverse relationships and attempt to recommend an actionable, and ethical, pathway for “scientific practice,” from the collection of samples to the presentation of findings to archaeological collaborators, funding providers, and, ultimately, the broader public.

Do we really need “experts?”

“Scientific practice” in archaeology is today linked to a growing specialization of researchers within the discipline, not only in the academic sphere but also within commercial archaeological units. This is not a new phenomenon, and archaeobotanists, archaeozoologists, and geoarchaeologists have been regular members of excavation and archaeological departments for a number of decades. However, the proliferation of new methods, including ancient DNA analysis, proteomics, remote-sensing, and a range of new chronometric and mass spectrometry-based methods (from optically stimulated luminescence dating to inductively coupled plasma mass spectrometry), among others, has meant that the number of potential specialisms is greatly increasing. Moreover, whereas archaeobotany and archaeozoology have frequently been utilized by those who would describe themselves as “archaeologists,” investigating a particular temporal and geographical question (e.g., Fuller et al. 2011), the practical knowledge required by newer applied sciences, especially if they are to meet the rigorous standards set by the parent disciplines, has often led to a separation between excavators and curators, on the one hand, and the specialists with whom they collaborate, on the other.

This division leads to issues on both sides. Methodological specialists often validate their results on the basis of statistical, biological,

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chemical, or biogeochemical parameters inherited from the application of their methods in the natural or earth sciences. In these parent disciplines, experimental designs can be constructed to control the number of variables, or biological or technical replicates can be implemented in order to add statistical weight to generated findings. Applied to archaeological contexts, however, such approaches may fail to consider issues of taphonomy, preservation, sample scarcity, context, and chronology, which often remain unexplored by methodological specialists. For example, although measurements of ancient DNA, fatty acid residues, or bone collagen may well meet appropriate scientific quality controls, very different conclusions will be reached depending on what is understood regarding their date or cultural context. Additionally, excavators and curators are often left wondering why specialist methodological papers, that seemingly ignore long-held arguments and knowledge in archaeology, are successfully published in high-impact journals. Finally, on a practical basis, specialists can fail to take into account cultural, political, national, post-colonial, and other tensions involved in the sampling and export of sensitive material culture and human remains in their laboratories or the field.

Similar risk to scientific practice comes when excavators and curators are content to simply send off samples to a scientific “black box,” located in a different department or country, without making adequate attempt to understand the potential methodological pitfalls involved in specialist studies. This can lead to the idolization of “data” as *de facto* support for existing theoretical and political biases. This means that innovative methods and data can fall into circular traps where biased research design leads to biased findings, doing little to advance archaeological knowledge. Excavators and curators also risk making decisions on the curation and provision of material that can hinder scientific advancement. This includes the facilitation of a method that may obliterate material that could have been utilized by another perhaps superior method, and the provision of sample sizes that are too small to provide effective results, leading to doubt in the method and the needless destruction of samples. Alternatively, seeing the vast growth and refinement of archaeological science techniques,

they may be reluctant to provision samples to researchers in the hope that a better approach may be just around the corner, an attitude which in itself may hinder methodological advancement. As such, a key challenge in scientific practice is to address how, and to what extent, divided “experts” in archaeology and archaeological science can fruitfully combine to produce truly novel understandings of the past.

Archaeological science in a world of “alternative facts”

“Scientific practice” does not just involve relationships between excavators, curators, and methodological specialists, however. Archaeology as a discipline is increasingly judged on the relevance of its research output to political agendas, economic development (e.g., tourism), and its interest to the general public. This instantly places pressure on researchers, especially in regions, countries, or institutions with limited funding, to make their projects and results more attractive to these interest groups. As a result, at least in part, archaeological science is forced to move beyond a straightforward position of experimental verification and fact-making, and address what happens to their data and arguments in the “hands of others” (Latour 1987), such as the media and politicians.

At a time when the public in many regions of the world seems increasingly willing or susceptible to accepting “facts” conveyed by politicians, media outlets, or interest groups, often with little regard for verification, the “hands of others” are increasingly prominent in archaeological scientific practice. On a political level, and notably still relevant today, Latour discussed 20 years ago how climate change policies in the United States, and the scientific information used to support them, change swiftly between alternating Republican and Democratic administrations (Latour 1993). Archaeology’s growing interest in the past impacts of climate change and anthropogenic alterations by human societies through time may not fit with the views of the governments or private sector organizations that support research, with implications for funding and research orientation. Similarly, while

archaeological applicants to the National Science Foundation are judged primarily on how their research can benefit America, with titles often individually ridiculed among the House of Representatives (Mervis 2014), archaeological applicants to the Deutsche Forschungsgemeinschaft in Germany are encouraged to take a “global” approach. Such examples demonstrate the contrasting present-day political outlooks of these nations and the effect they can have on scientific funding and practice.

In a broader sense, funding bodies and political groups, with limited funds to distribute, can often favor individuals and projects with a “story” that can be sold to the public and news outlets and thus justify expenditure. It is far easier to do this with broad-sweeping statements, that overstate the realistic contribution of the produced data, than it is with specific, more critically interpreted studies. However, such research has the potential to damage scientific credibility, at least in the presentation of the resulting data. Moreover, it is much less likely that a funding body will support basic methodological developments when compared to the application of methods to a period or region of public interest. Such propensities can hinder the discovery of methodological pitfalls, and prohibit the refinement of archaeological science techniques.

A recent prominent example of archaeological science being drawn into “story-telling” can be seen in the attention surrounding the discovery in the United Kingdom in 2012 of a skeleton suggested to be that of Richard III, former King of England. While the contextual, genetic, and forensic evidence for this identification is no doubt strong, the interpretive caution often expressed by archaeological scientists was in some part swiftly lost in the production of a narrative played out by news outlets and the wider public (King et al. 2014; Lamb et al. 2014). Similarly, in playing to a public and media fascinated by “firsts,” recent archaeological science has at times devoted inordinate resources to the recovery and analysis of finds suggested to be the earliest in some particular category, regardless of the sometimes dubious significance and scientific merit of such achievements.

Archaeological science in action

Scientific practice in archaeology is thus enmeshed within the social, political, and economic context in which it unfolds. Science is not a separate, “pure” sphere in which the practice of “data” production is disconnected from the rest of society. Instead, interpretations, conclusions, and project proposals will be influenced by individual archaeological and museum collaborators, institutional and political administrations, and funding bodies. So how can we put robust archaeological science approaches into action? Essentially, we must understand the interest groups involved at every stage in the handling of scientific practice, recognize these potential biases, and provide workable and transparent criteria by which to evaluate and interrogate results.

Successful integration of archaeological and methodological expertise is aided by the bringing together of these two types of specialties within individual projects, departments, and institutions. On a more individual basis, success is also aided by the initiative of nonspecialists striving to be genuinely involved and engaged with the process of applying scientific methods to research material they provide to specialists, including grappling with the method’s potential pitfalls and challenges. Finally, scientific specialists should provide clear and transparent guidelines to educate potential users about their methods so that everyone can be involved in validating the scientific process. One good example of this is the recent release of “Organic Residue Analysis and Archaeology” by Historic England (2017), in combination with specialists across the United Kingdom.

Within this perspective it is also important that projects with an archaeological science dimension are developed collaboratively, with excavators, curators, and methodological specialists all being involved at an early stage wherever possible. Sampling and curation of material should be performed with a dialogue between the institution at which it is stored, previous researchers who have utilized the same material, and cultural and political interest groups where relevant. The placement of new methodologies in an accessible format, such as on websites (e.g., University of York 2016), with attached videos and sampling guides,

allows excavators, local collaborators, and curators to actively seek collaboration and understand how new methods can benefit their collections, balancing out the currently common practice in which the impetus for collection sampling comes from methodological specialists and their independently developed research agendas. In some cases it may even be that these individuals can undertake the sampling themselves, with specialist guidance, placing them at the center of the process of data production from the very beginning.

In the wider political and economic sphere, it remains a reality that funding and research publicity will be shaped by political and economic agendas. Where possible, as with scientists across other disciplines, it is important to publicize the realistic positives and negatives of any given approach, both within the academic sphere and to the international public. While this is a hard thing to action given that academic careers depend on securing funding and generating successful outcomes, this can be helped by ongoing discourse among archaeologists and methodological specialists, and indeed journalists, regarding what is possible and what is not. Publication of “replies” to high-impact papers that have overstretched their mark, the development of criteria by which reviewers and journalists should question spurious interpretations, and the emphasis on methodological development where funding is not such a constraint are potential avenues through which to achieve this.

Scientific practice in archaeology is an area of exciting potential and notable challenges, significantly enmeshed with current social, political, and economic agendas and dialogues. Ethical and effective scientific practice demands engagement by both scientific specialists and archaeological researchers responsible for excavation and artifact curation. Engaging in scientific practice does not mean permission to overlook archaeological responsibilities in pursuit of an untethered and objective natural sciences approach. As scientific practice in archaeology grows and diversifies, the discipline’s commitment to a broader anthropological agenda that prioritizes diversity, responsibility, and engagement with both mainstream and marginalized interest groups should remain a key priority.

SEE ALSO: Archaeological Sciences; Archaeology and the Present; Authorized Heritage Discourse; Bioarchaeology; Ethics in Conservation; Heritage and Politics; Heritage and Society; Heritage Ethics; Philosophy of Science; Plurality and Multivocality; Public Archaeology

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Scientific Revolutions

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Efforts to rethink problematic generalizations about a supposedly singular (*the*) Scientific Revolution may figure among the most important ways in which characterizations of the arts and the sciences as opposed and mutually incompatible “two cultures” are being called into question today. The publication of Thomas Kuhn’s *The Structure of Scientific Revolutions* ([1962] 1970)—and cross-disciplinary discussions of the issues it raises—marked turning points in this development; and in the emergence of numerous novel interdisciplinary trading zones between the arts, humanities, and material and life sciences, evidenced throughout this *Encyclopedia*. Many aspects of Kuhn’s work have parallels in earlier and contemporary scholars. Many aspects of Kuhn’s work had predecessors and parallels in the work of some of his contemporaries. However, it was most remarkable in its original contexts, and remains valuable to revisit for a variety of reasons, including the contributions that it made to appreciating the importance of contextual approaches to rethinking “scientific revolutions” (including those happening today).

In order to contextualize this entry, it bears underscoring that it was not until the emergence and spread of remarkable interest in the cross-disciplinary significance of issues raised by contrasts between logical positivist and logical empiricist philosophies of science, and Kuhn’s “new philosophy of science” (or history and philosophy of science), that philosophy of science became a key area of archaeological specialization; and archaeology became a key area of specialization in the history and philosophy of science (see, for instance, PHILOSOPHY OF SCIENCE). Issues that Kuhn’s conception of “scientific

revolutions” raises have become important trading zones: for instance, within fields as a model of disciplinary history (e.g., archaeology); between fields (e.g., the History of the Philosophy of Science (HPS), science technology studies, culture studies); and as new fields in their own right (e.g., historical epistemology).

All this underscores the huge range of the intellectual and social contexts of the topic of “scientific revolutions,” and motivates our focus here on: key dimensions of the topic of philosophical implications of “scientific revolutions;” change in approaches (relating to Kuhn’s work) to “scientific revolutions” as a paradigm for archaeology’s disciplinary historiography, and to insights that the notion of a singular (*the*) Scientific Revolution calls for continual rethinking; and the dynamics of current foci and future directions of work, relating to archaeology’s bearing upon challenges of rethinking incommensurability and taking the arts and sciences equally seriously.

“Scientific Revolutions” in long-term historical perspectives

According to Copernicus (1473–1543), the concept of a “revolution” (a term for a form of movement) becomes a key principle in the sun-centered model he put forward as an alternative to predominant Ptolemy (100–168 CE) and Aristotle (385–323 BCE) based scholastic models of the earth-centered structure, composition, and forces of the world. It is not likely that a conception of the philosophical significance of such changes developed until the end of the Enlightenment, especially, in the work of Immanuel Kant. Kant’s *Critique of Pure Reason* ([1781] 1999) and *Critique of the Faculty of Judgment* ([1780] 1955) stressed the philosophical significance of the “Copernican Revolution,” and described it as a revolution in “world view” or “mode

of thought”—with direct bearing upon such complex philosophical questions as those about the dynamics of humanly constructed “phenomena” and “things in themselves;” about how humans attribute meaning to experience; and about the ethical significance of human capacities to treat one another as “ends in themselves” rather than “means to ends.” This range of ideas has indubitably contributed to the interest in and the liveliness of debates about Kuhn’s conceptions of “the structure of scientific revolutions” and “paradigm incommensurability.”

The eighteenth and nineteenth centuries saw science become an historical study area, and the emergence of polemic over continuity (gradual) and discontinuity (punctuated) models. Discontinuity models went out of favor for a variety of reasons, including implications for foregrounding conflict. Continuity models marginalized conflict, and conformed to positivist philosophies’ characterization of the history of science as a gradual cumulative process whereby errors are corrected and theories move towards supposedly timeless truth. All this was called into question by Alexander Koyré, who figures centrally among twentieth-century critics of such positivist arguments, as that historical facts somehow “speak for themselves.” Koyré is widely recognized as the scholar who coined the concept of the “scientific revolution” (Kuhn [1962]1970). Koyré (1965) characterized this revolution in terms of the undermining of traditional cosmologies; and the emergence of a geometrical picture of the universe; traditional earth-centered celestial and sublunary spheres were replaced by a universe in which geometry united astronomy and physics. In Koyré—as in Kuhn—these processes are not at all characterized in terms of notions of a supposed replacement of so-called irrational by more rational modes of thought. Koyré stressed how the spread of beliefs in the authority of mechanical natural philosophy and experimental science became linked to highly problematic images of individual psychology and society based on interpretations of Newton’s *Principia Mathematica* (1687) and John Locke’s (1632–1704) *Essay on Human Understanding*. Central motifs in these images included “an atomic” psychology and sociology that reduced human life ways and societies to individual and clusters of atoms attracting and repelling one another.

Change in approaches: three examples

Kuhn’s work in context

For many working in the humanities and social sciences during the 1960s through the 1990s, it may have been difficult to imagine an era when their area of disciplinary specialization had not been characterized as experiencing “crises over representation” and deep and far-reaching “paradigm change”—comparable at some level with what Kuhn described in *The Structure of Scientific Revolutions* ([1962] 1970). The second half of the twentieth century saw discipline after discipline split its goals along axes of such dichotomies as those of art–science–nature–culture, and materiality versus the meaningful. Debates over archaeological methods and theory parted ways around processual and post-processual responses to such processes as those of David Clarke (1973), who characterized it as the field’s “loss of innocence” and “critical self-conscious phase.” Much disagreement revolved around archaeology’s classification as a “human science” or a “natural science” (Preucel 1991, 17).

Polemic over such vexed options did not develop in a vacuum. The twentieth-century history of the arts and sciences has often been seen as marked by two “crises over representation.” One centered on knowledge concerning “nature,” and was marked by crises over clashes between positivist philosophy and Einstein’s Relativity Theory. The other centered on knowledge concerning “culture,” and was marked by crises over clashes between positivist claims about value-neutrality and the extent to which deeply value-laden problematic interpretations of history and cultural diversity were linked to “colonialist,” “nationalist,” and “imperialist” ideologies. Relativity Theory went against the grain of Newton’s “laws of matter and motion” and positivist presuppositions about a unified hierarchical system of sciences, grounded in the objectivity of “primary”—quantitative versus the subjectivity of “secondary”—qualitative data; about independence of collecting, describing, and analyzing data from interpretation and theory; and about progress.

Until Kuhn’s “new philosophy of science”—or “history and philosophy of science”—the most influential responses to these problems were those

of logical positivist scientists and philosophers. While these scholars disagreed on many points, in general, the aims of what became known as the “received” or “standard view” were to analyze scientific concepts, relationships between evidence and theory, and scientific explanation on the basis of specialized language and logic. Emphasis fell on dividing scientific knowledge from other types of knowledge; fact from values; observation from theory; and contexts of discovery from theory falsification or confirmation (Salmon 1992). One of the most famous and controversial methods put forward is that called the “hypothetico-deductive” method, which centres on distinguishing between formulating a hypothesis, deducing a prediction that is amenable to observation, and performing an observation to see whether it confirms or falsifies the hypothesis.

For Kuhn, there were direct connections between obstacles the “standard” view posed for understanding revolutionary science change; and for creating a satisfactory philosophy of contemporary science. The history of science was, in Kuhn’s terms, an anomaly for the “received” philosophy of science. Kuhn clearly agreed with logical positivists and logical empiricists on key problems with traditional positivism and empiricism; and appreciated the extent to which the former scholars’ priorities grew out of convictions they developed under life-threatening conditions in Nazi-occupied Europe. However, Kuhn was concerned about the “standard” view’s a-historical (synchronic) picture of science. Its preoccupation with logic eclipsed dynamic diachronic relations between the contents and cultural contexts of science. With Kuhn, emphasis falls upon philosophical implications: the “standard” view was not able to account for revolutionary changes in the past and in the contemporary world. With Kuhn, changes in science that go against the grain of hitherto predominant paradigms for epistemology (methodology) and ontology (theory) call for “revolutionary” change in our understanding of knowledge, in general. Kuhn stressed that “scientific revolutions” are intrinsically historical, and that the historical contingency of science is a strength, not (as so often presupposed) an impediment.

Kuhn’s “scientific revolutions,” “paradigm,” “normal science,” and “incommensurable world views” all evidence these orientations. For Kuhn,

innumerable revolutions had occurred, especially in the formation of disciplinary specializations as paradigms. Scientific revolutions are not things that happened only in the distant past—they are happening today, with implications for change in our understanding of knowledge and the world we live in. From one day to the next, we may be responding to a “different world.” While the notion of a “paradigm” has many connotations, two figure especially centrally in the distinction Kuhn drew between the plurality of “scientific revolutions” and the “structure of scientific revolutions.” On the one hand, the concept refers to the “form of life” of a community. A research paradigm is what a scientific community shares—educational backgrounds, values, skills, and understandings of expertise and professionalism. On the other hand, the concept refers to exemplary models and normative criteria as resources that guide problem solving in “normal science.” For Kuhn, when a “paradigm” becomes seen as unable to solve decisive “puzzles,” it becomes an “anomaly.” Under “revolutionary” circumstance, the puzzles at issue become the foci of work on a new paradigm, and the old and the new paradigms concern “incommensurable worlds.”

Kuhn continued to work on diversity among disciplinary histories; and on what might be meant by “incommensurate worlds.” He stressed the importance of specialization to the sustainability of a new paradigm. In turn, specialization raises questions about diversity among the ways new specializations interpret a new paradigm. Kuhn focused particular attention on “incommensurate worlds” in *The Road Since Structure* (Kuhn, Conant, and Haugeland 2000): for instance, what is meant by the Copernican statement that “planets travel around the sun” cannot be expressed in the terms in which the Ptolemaic statement “planets travel around the earth.” This contrast compares with the ideas of a “gestalt” shift and “seeing aspects anew” of Ernst Gombrich and Ludwig Wittgenstein.

*“Scientific revolutions” as a paradigm
for archaeology’s disciplinary
historiography*

For many working in archaeology during the 1970s through 1990s, it may have been difficult to

imagine an era when the field had not been experiencing “crises over representation” and deep and far-reaching “paradigm change.” At issue was not the idea that research had been previously static. Emphasis fell on rates of change; and on the implications of new scientific technologies for addressing questions that had formerly been seen as intrinsically irresolvable, or not asked. Many categories, chronologies, and theoretical models that were previously treated as being of self-evident utility became characterized as belonging to traditional “schools of thought,” and as “anomalies” in the light of new findings and orientations. It was a period when the history and philosophy of science became a key area of archaeological specialization; and archaeology became a key area of specialization in the history and philosophy of science. It was the period when processual and post-processual paradigms diverged. Lewis Binford grounded much of his “new archaeology” in logical positivism and logical empiricism. Colin Renfrew sought variously to integrate aspects of these paradigms with insights drawn from Kuhn and David Clarke. Clarke’s (1973) paper “Archaeology: The Loss of Innocence” marked a turning point in the history of processual and post-processual paradigms. For Clarke, the adoption of scientific instruments and laboratory procedures developed during the two World Wars, vastly expanding available archaeological information. New technologies—in particular carbon-14 dating—brought light to anomalies in hitherto normative paradigms. They caused a “loss of innocence” about the ways in which archaeological materials had been used to address questions about the past. Clarke and Renfrew focused particular attention on anomalies in traditional pictures of European prehistory. The new dates showed that numerous events that had been treated as contemporary were separated by many centuries. The issue was not just about having dates wrong. The many arrows that had been drawn across maps of European prehistory to portray theories about the spread of peoples, ideas, and inventions from the supposedly “more advanced” Near East and Aegean to central, western, and northern Europe turned into anomalies.

In these views, archaeology was experiencing what Kuhn called “revolutionary” science change. In Clarke—as in Kuhn—plurality of scientific revolutions shaped disciplinary histories.

Clarke (1973) may have envisaged what he saw as the three key “thresholds” in archaeology’s disciplinary history along these lines—those of “consciousness, self-consciousness and critical self-consciousness” about archaeology’s philosophy of science. With Clarke, there is no such thing as a methodology independent of theory. Perhaps with Clarke (as with Kuhn) new paradigm sustainability hinges upon fostering lines of specialization (e.g., pre-depositional and depositional theory, post-depositional and retrieval theory, analytic theory, and interpretive theory).

Rethinking the notion of a singular scientific revolution

Up to this point, we have not stressed that the notion or image of *the* (singular) Scientific Revolution has a much longer and more problematic history than “scientific revolutions.” It is no coincidence that the above-mentioned changes have occurred in tandem with increased awareness that the former is a highly problematic image, calling for serious cross-disciplinary critical examination. Throughout much of the nineteenth and twentieth centuries, that image figured paradoxically among both the most and the least historicized presuppositions shared across the most influentially opposed theoretical traditions in the humanities: the most historicized, because it was assumed to figure among the prime movers of modernity, and was used as models for interpreting the diversity of cultures (and even human origins); and the least historicized, relating to notions of dichotomized truth versus contingency, and assumptions that contexts were already self-evidently known. Issues raised by Kuhn threw sharp light on these anomalies. It is unlikely to be a coincidence that major changes in approaches to these issues have been accompanied by efforts to rethink the problematic role that the image of *a* (singular) Scientific Revolution has played: for instance, as a key motif in generalizations about the supposed unity and distinctiveness of so-called western culture; and as a presupposition at the heart of such dichotomies as those of objectivity versus subjectivity, nature versus culture, and art versus science.

Today, much change in what discussions of “scientific revolutions” (and of the history and philosophy of science, in general)

emphasize is informed by the light these efforts are throwing on new questions: To what extent do the above-noted dichotomies (as well as highly problematic generalizations about “incommensurability”) hinge upon problematic pictures of both science and the supposed “disenchantment” of art history? What have been the circumstances under which responses to “crises over representation” have given rise to notions that we are forced to choose between such vexed options as either a deterministic order and Archimedean picture of knowledge or absolute chaos and hyper-relativism? To what extent have these (and related vexed options) eclipsed alternative options, and what are their implications for appreciating the jointly epistemic and ethical significance of incommensurability and alterity?

Current approaches and future directions

Even our brief examination of three manifestations of change in perspectives on “scientific revolutions” points to the continuously widening variety of approaches, and implications for future work. For instance, since the 2000s, the concepts of a “palimpsest” and “hybrid” have become widely used as tools for research on issues that have been eclipsed by divisions between studies of how things are made (their materiality) and studies of what things mean. These notions have special advantages for fresh approaches to the role of “practices” (or “use” in the widest sense of the term) in the dynamics of the material and the meaningful, and to the question of what is meant by a “context.” They invite us to explore the roots of problematic generalizations about so-called other world views (or modes of thought); and to appreciate the epistemic and ethical significance of experiences of incommensurability or alterity. Current studies that are engaging with the dynamics of materiality and meaning differ along an extraordinary variety of lines (see, for instance, MATERIAL CULTURE). However, one feature they often share with one another—and with Kuhn et al. (2000) and Emmanuel Levinas

([1961] 1979)—is a remarkable shift away from Archimedean notions of evidence. Instead, they envisage recognizing alterity and incommensurability as the very evidence that makes our understandings and experiences of evidence possible.

SEE ALSO: Philosophy of Science

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Substances and Materials

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Philosophers have theorized *substances* in many different ways, the range of which holds conceptual and practical implications for archaeological study and historiography. In general philosophical terms, one can equate substance to the primary entities of an ontological paradigm; that is to say that substances encompass the foundational components or abstract elements of a metaphysical framework. Descartes (1997), for instance, is well known for foregrounding body–mind dualisms and distinguishing the material substance of the world from the mental substance of thought. Thus, substances need not be strictly *material*. The “substance” or essence of abstractions or spirits, for instance, might be considered immaterial. In the more specific sense of an ontological framework that places primacy on particular substances (e.g., “substance ontology”), they are considered the basic materials, building blocks, particulars, or atoms from which artifacts and the world are produced, and are often qualitatively differentiated as distinct types of things or stuff (Robinson 2014). The notion of substances as different types of materials or stuff is commonplace in archaeological science and practice; indeed, it has strong resonance with molecular chemistry and how many of us conceptualize the aggregation of different elements in comprising durable things.

Ontological frameworks that emphasize the primacy of different kinds of substances stress the *intrinsic* attributes, dispositions, or nature of something. These dispositions are generally considered to be stable and a priori or independent of relations with other entities. In the context of archaeological lithic analysis, for instance, one might think of obsidian as having the intrinsic attribute of conchoidal fracture—that is, the stone holds that fracturing property before it was

ever struck by some other hard object to produce a tool, waste flake, or scar. An ontological framework that gives primacy to substances with inherent and predictable properties has significant epistemological implications for archaeology. For instance, conceptualization of obsidian as a particular kind of material substance with stable fracturing properties allows archaeologists to apply practical and technical understandings of stone tool production derived from contemporary *experimental archaeology* to make inferences about how people fashioned the same material in the past or the chain of operations of tool production. Mechanical understandings of substances as holders of predictable behavioral properties also open space for specific conceptions of human agency in shaping the world, given the degree to which they can be worked, crafted, and arranged according to human intentions, plans, or desires. Yet ontological understandings of substances that privilege their inherent nature and stable attributes can also lead to ahistorical and presentist arguments about the past, such as the view that “precious metals” like gold and silver are essentially valuable, regardless of cultural and social context.

Substance ontologies are often contrasted with *relational ontologies*. Relational ontologies privilege interactions and make shared relations among metaphysical entities more foundational to the nature of being than essences or individualized particulars with inherent attributes. With respect to archaeology, it is important to note that relational ontologies would place fundamental emphasis on the situations and contexts in which things occur and articulate with others. For instance, one might think of a marble sculpture and an organic grain of rice as composed of different kinds of stuff—one that is inherently more enduring and stable that comprises the sculpture and another that is inherently impermanent and fragile that comprises the grain. Yet, in certain contexts—for example, where there are high amounts of acid rain and sulfur dioxide air pollution—marble quickly disintegrates, and in others—for example, waterlogged anaerobic

conditions—organic material may persist with minimal alteration for thousands of years. Their properties are contextually or relationally dependent, and thus one kind of material is not innately more durable than the other by virtue of its substance or essence. While philosophers inclined toward a substance ontology may argue that these properties are simply “secondary” to an underlying (unchanged) substance that, by its nature, affords such apparent transformations, relational ontologies stress the relationships themselves as fundamental: Shifting relationships change substances.

By calling attention to relationships, relational paradigms are amenable to process-based philosophies that foreground interactions and consider the nature of being as fundamentally dynamic. They are often evoked with the concept of an *assemblage* developed by philosopher Gilles Deleuze. Jane Bennett (2010), for instance, argues for the “vitality” of matter in considering material *actants*—a term borrowed from philosopher Bruno Latour to refer to entities that are sources of action and often *mediate* or “modify a state of affairs” (e.g., Latour 2005, 71)—as part of broader assemblages that dynamically give shape to the world and contribute to human social and political histories. Assemblages are temporary configurations of heterogeneous elements that, through their historical configurations, produce *emergent* outcomes—which is to say that their effects are not merely the sum of their parts, nor are they reducible to individualized properties. Bennett uses a blackout as an example, suggesting that an electrical blackout might productively be considered the outcome of the specific conjuncture of a multitude of energy consumers, material networks (e.g., electrical transmission wires, downed power lines), “reactive” power that is necessary to maintain transmission voltage (but that dissipates over long distances), and government regulations that do not incentivize energy providers to generate “reactive” power over “active” power. Here it is important to note that theories of causation and emergence might productively consider substances and relations in tandem.

The work of Bennett and others (e.g., Coole and Frost 2010) is representative of a suite of scholarship, often termed *new materialism*, that de-privileges humans in giving shape to

social history and artifacts. These frameworks have explicitly questioned the exceptionalism of human agency by positioning human actors within an assemblage, collective, web, or grid of other material things, substances, or forces that affect activities, social relationships, and historical outcomes. In this sense, renewed theorization of substances and materials as dynamic and active has called attention to the limits of human agency and how its theorization might be decoupled from longstanding links to individual, rational actors. Moreover, much of this scholarship stresses that things are not fully reducible to the meanings that people associate with them, and that the active qualities of materials need not conform to human will or intentions. These emphases are compatible with other anthropological and archaeological approaches that have stressed the embeddedness of humans and their environments, such as those deriving from phenomenology. The anthropologist Tim Ingold (2000, 77), for instance, has argued against the notion that humans simply impose mental templates or designs onto materials in craft production; instead, he suggested that the fashioning of artifacts should be considered a process of “growth,” similar to how raising crops or animals involves interactions among a multitude of materials and organisms (rainfall, pests, etc.) that practically constrain, condition, and shape material outcomes. Artifacts “emerge—like the forms of living beings—within the relational contexts of the mutual involvement of people and their environments” (Ingold 2000, 88). Such concerns explicitly call attention to how the dynamics of substances are important to the crafting of material worlds and historical processes, opening up a range of possibilities for the archaeological sciences to contribute to broader conversations in the humanities and social sciences.

Archaeology, of course, has a long history of considering the role of environmental materials and relationships in shaping human history. For instance, the “economic approach” advocated by Grahame Clark (1953) in the mid-twentieth century emphasized the environmental constraints and possibilities related to human subsistence choices, suggesting that cultural development increasingly expanded the possibilities for economic activities while simultaneously calling attention to feedbacks between these activities

and physical ecological limits on production. Moreover, the New Archaeology that developed throughout the 1960s and 1970s borrowed heavily from ecological paradigms of anthropology (e.g., cultural ecology) and often considered the distribution of subsistence resources (e.g., water and game) as giving shape to cultural land-use and social organization. In these frameworks, the dynamics of the environment, such as climate change, were frequently linked to cultural change as resources shifted and people were forced to adapt. Renewed emphasis on the dynamics of substances, or more precisely *relational substances*, have reinserted the importance of material dynamics into the mechanisms of historical change—although often at different scales and with more contextual nuance and complex determinative logics than earlier approaches.

Paradigms that consider substances to be “vital” (*sensu* of Bennett 2010) have called attention to how the “actions” of materials frequently provoke or require subsequent human actions. For example, Ian Hodder (2012) has cogently argued that once humans begin to depend on specific materials as resources—such as clay for constructing walls—they become trapped, or “entangled,” in relationships of dependencies in which the properties and behavioral interactions of substances condition human activities. As construction materials weather and erode, they force humans to maintain them and create relationships of “care, regulation, and discipline” (Hodder 2012, 78). In that sense, it has been argued that the interactions of materials have a form of “primary agency” in shaping human social history.

Theorizations of historical processes that stress the significant role of substances in engendering certain social activities open up important space for the archaeological sciences to contribute to “new materialist” historiographies. Many analytical techniques of archaeological science document the past actions of materials—that is, how they physically behaved in specific contexts. For example, by examining soil and sediment structure, texture, and composition, geoarchaeologists can document the alteration or stability of land surfaces, the relative energy involved in water and wind transport and deposition, and the movement of mineral matter from source to

destination. Similarly, soil micromorphological analyses document a range of soil features and formation processes that further underscore the transmutation of materials in archaeological contexts, documenting the weathering of minerals and the formation of others, the shrinking and swelling of clay, and the translocation of materials in soil profiles. Such observations effectively detail the dynamics of soil as an outcome of interactions among heterogeneous constituents and provide important links between recording the properties of materials and the social history of landscape production.

Placing emphasis on the “actions” of relational materials and the cultural contexts in which things are differentially valued might open fertile ground for new emphases in archaeological historiographies that rely heavily on archaeological material sciences. Borrowing the term from geomorphological studies, Bauer and Kosiba (2016) refer to a process of “entrainment,” whereby materials that are “caught up” in the flow of human activities have the potential to affect politics and social change. In the context of the South Indian Iron Age (1200–300 BCE), for instance, they argue that the cultural value placed on herd animals heightened the social and political consequences of soil erosion, which shifted the distribution of herding resources and contributed to the emergence of social inequalities during the second and first millennium BCE. The current interest in relational ontologies and process-oriented philosophies toward materials might productively call attention to what things physically do in specific contexts, as well as how their social and political effects are also context dependent, conditioned by historical values and differentiated perceptions and understandings of environmental phenomena among humans. Such frameworks open opportunities for explicitly considering the historical process as neither exclusively culturally nor environmentally determined.

SEE ALSO: Experiment in Archaeology; Geoarchaeology; Making and Skill; Material Agency; Material Culture; Material Entanglement; Micromorphology; New Materialisms

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Symmetrical Archaeology

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Throughout the history of our discipline, qualifying adjectives have been added to archaeology in order to distinguish a particular approach or doctrine and its adherents from what was framed, whether critically or rhetorically, as the “normative mode” of practice, of interpretation and formulating questions. Symmetrical archaeology did not set out on this familiar path. It began as a modest proposal to remember those increasingly neglected nonhumans relegated to the wings as props for humans-among-themselves, what archaeological practitioners viewed as the privileged protagonists in the “social” spectacles that comprised past worlds (Olsen 2003). Symmetrical archaeology eschews that critical gesture of dialectical one-upmanship that would relegate other practices, concepts or questions to the realm of the outmoded (González-Ruibal 2007) and avoids that disciplinary amnesia associated with such a paradigmatic image of progress. Rather than exaggerating differences with other subdisciplines, symmetrical archaeology excavates to what is common for archaeologists everywhere—things. Thus it is not a unified theoretical platform. It can best be characterized as a series of propositions for approaching ceramic-laden fields, ruined Byzantine structures, or buried middens, and generating more faithful, more inclusive accounts where things, what has become of pasts, are recognized as mediators rather than mere intermediaries; where pasts are not separated off from any present by ruptures or revolutions (something reinforced by an image of a linear, successive, and externalized time), but linger amidst perishing, gather amidst dispersion, and endure amidst transformation within a dynamic ecology of coextensive actual entities in the present. Whether practitioners choose to see symmetrical archaeology as eschewing that oversimplification of diverse entities into two purified

domains or as an altogether different metaphysical commitment, it is worth repeating that the adjectival label was always recognized as provisional (Witmore 2007, 547; Olsen 2012, 223).

Symmetrical archaeology derives its adjective from the principle of symmetry. If we are to avoid a double standard where the scientific practices behind the Clovis-first hypothesis (a now disavowed consensus, which held the prehistoric Clovis culture to represent the first peoples in the Americas) are treated a priori with utmost certainty, while indigenous methods for detecting a deeper ancestral presence in North America are regarded with absolute incredulity, then truth and falsity, fact and belief, successes and failures, the new and the outmoded have to be explained in the same terms. Whereas the first principle of symmetry remained asymmetrical by seeking explanation in the realm of society, a more generalized principle of symmetry boldly trudged across the great divide to include what had been purified as “nature” and left to the natural sciences (see Latour 1993, 91–6). Symmetry serves to remind practitioners not to decide in advance what role various entities play in a given situation by imposing arbitrary hierarchies of value or preformed dogmas concerning the nature of the real. Reservations about the term “symmetry” have been voiced repeatedly, and misunderstandings abound (see Olsen and Witmore 2015). It is not that everything goes, but what is relevant in a given situation cannot be sorted out without substantial labor. Symmetry is best conceived as an agnostic disposition, a guideline, a principle, or even an attitude (Shanks 2007); it is not an ontological maxim that undergirds all being. Symmetry does not imply that all entities exist equally—asymmetries are legion—rather it suggests that all entities be equally granted dignity as things.

Initial forays into symmetrical archaeology regarded things, “those enormously varied physical entities, ... [as] beings in the world alongside other beings such as humans, plants, and animals” (Olsen 2012, 212). Positive emphasis was placed on “thing” in its etymological sense of

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“gathering.” Even the smallest of the individual limestone blocks within the polygonal walls of the Argive Aspis is a co-realization of limestone form in relation to other forms, the purpose that is the pride-infused wall, and skilled stonemasons with hammers and chisels. Relations, moreover, between stonemasons and polygonal walls are no more and no less important than the relations between individual blocks, foundations and tree roots, or pride-infused enclosures and the Argive polis. If any of these beings makes a difference in a given situation, then it is “actant,” and an actant is no more and no less important than other actants at the start of an analysis. While this analytical leveling opened the door for understanding the diverse mediating roles of nonhumans, it left it ajar for others to reassert orderings of the world on the basis of pre-ordained taxonomic divisions, whether as humans and the rest or vital and inert entities, even though symmetrical archaeology patently rejects such radical separations. It is also the case that an emphasis on relations and agencies is asymmetrical so long as it misses other properties of things—not only those aspects that surface *for us* or *for others*, but also what is intrinsic to things, the *in itself* (Olsen 2010).

Symmetrical archaeology radically reconfigures the definition of things, not as objective matter against subjective qualities, not as the relational opposed to nonrelational, not as the nonhuman counterpoised to the human—things have no opposites—but rather as autonomous entities or units that cannot be broken down into their components or reduced to their effects (Olsen and Witmore 2015, 191; Witmore 2014, 4). Neither materials nor ideas nor abstractions are to be relegated to the sidelines, for this would directly violate the principle of symmetry. Former gateways and streets are no more and no less things than the goddess Demeter or the psycho-political wellbeing of a Hellenistic polis. While one thing is not derivative of another, this does not imply that all things exist equally. Polygonal walls and limestone exist differently from erstwhile stonemasons or microorganisms precipitating on the seafloor 100 million years ago.

Symmetrical archaeology does not provide a ready-made theory to apply across diverse situations. Things resist our attempts to grapple with them, to articulate them, or to explain any

of them in terms of something else. Thus, it stands in defense of the otherness and integrity of things against approaches that subject them to sameness, where, for example, an overemphasis on the construction of authority makes Chaco Canyon sound like Chavin-de-Huancabamba. This commitment is also related to an ethical issue of care and devotion to things for what they are in their own being. Symmetrical archaeology, therefore, aims to flush out idiosyncrasies by articulating the positive differences between the legion things present at these sites, which may lead to richer and more compelling narratives (Olsen 2012, 213; Olsen et al. 2012, 13–14).

Symmetrical archaeology asserts that archaeology studies a bewildering variety of things in the present rather than the human past through its material remains. It is a “fallacy of expression,” for any symmetrical approach, to situate the agency of Roman soldiers a priori behind what lies before archaeologists in an open field. Neither the past nor the material past is the starting point for archaeology; rather, the erstwhile angle is part of the solution. While this is partially related to a classic issue of assumed versus justified identifications of archaeological things, things do not gain their reality from elsewhere—succinctly, what has become of a Roman fort is involved in the realization of its past in the present. Symmetrical archaeology does not turn its back on humans or the past; rather it submits that the full price for any account of what was, tentative and risky as it is, must be paid. If abandoned surfaces cannot be reduced to an erstwhile equestrian barrack, animal enclosure, or ruin, then painstaking work must be done to explain one in terms of the other. In order to connect a portion of polygonal walling to the psycho-political wellbeing of a Hellenistic polis, significant labor must be invested and this work is always open to reassessment.

Narratives concerning the past, and even the material past itself, are what archaeology achieves. The question of how to proceed belongs to a wider field of possibilities, to the creative adventure that is archaeology. Because relevant questions surface in the course of our practices, our achievements should not be severed from the labor that led to them. Indeed, archaeologists do not stand apart from the world that they seek to better understand. Many early examples

of symmetrical archaeology were concerned with a problem-oriented set of emphases that included a focus on mediating roles of things within a localized process of doing archaeology. Symmetrical archaeology recognizes how every achievement is realized within a very specific ecology of practices, comprising institutions, instruments, affiliates, knowledge design, and the like, and some studies have gone to great lengths to demonstrate how the past is co-created with legion entities. Because the world cannot be reduced to a scheme where humans maintain a 50% share in reality, archaeological theories, stories and ideas comprise but a portion of archaeological labor and achievement. Succinctly, what things are willing to share regarding their erstwhile existence is best understood as a species of memory (Olsen 2012). Memory is an involuntary aspect or quality of things and is related to their own capacity for manifesting their pastness to us. Therefore pasts belong as much to middens or abandoned turf enclosures in a camp as to those PoWs or guards that archaeologists may seek to better understand.

Symmetrical archaeology is an inheritor of that longstanding archaeological aspiration to dig to what is fundamental as our objects of study, but not at the expense of sorting out what is real and what is not in advance. It aspires not so much to greater certainty as to making positive gains amidst every present uncertainty. Its stories are diverse, from gatherings of different times in the fabric of Greek city-states, Ethiopian landscapes of abandonment to material memories present in a PoW camp in Finnmark, Norway. Ultimately, symmetrical archaeology strives for an archaeology that is not subsumed to history, but is equal in scope and thus stands as both its complement and alternative.

SEE ALSO: Empiricism; History and Sociology of Science; Material Agency; Material Entanglement; New Materialisms; Realist Philosophies of Science; Time and Temporality

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Time and Temporality

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Archaeology can be defined by its emphasis on the time depth of its study, the importance of the passage of time, and material culture. To this we might add an interest in a multiplicity of narratives—in terms of both narratives that make space for multiple interpretations of material culture and narratives produced from things that tell stories of people that might not be accessible from more conventional histories. Time provides one means along which archaeologists can arrange and structure their narratives. The details of different time measurement systems will not be explored here, but the implications of applying these schemes will. Different methods for the documentation of the passage of time have often marked important developments in the discipline, in terms of our understanding of the natures of things and of writing about change and the causal mechanisms we employ. These developments have sometimes been allied to other areas of research: for example, the importance of Charles Lyell's work on stratigraphy and geological principles in the nineteenth century.

Archaeologists look for patterns in the distribution of material culture over space and time. These patterns are indicative of previous peoples' choices and behaviors, and preservation and excavation bias. Because all material culture exists and is studied in the contemporary world, archaeologists sometimes perceive that the spatial distribution of things is relatively simple to document. Reconstructing how things have existed over time outside our present experiences of them has presented more difficulties for archaeologists. How to represent and order the time dimension of archaeological study has therefore been one of the key themes of the discipline. This goes beyond the quest for the "first example" of this thing, or the "oldest known case" of that thing, though often it is "the firsts" and "the oldests" that

make headlines. The schemes that archaeologists use to order things along the time dimension of their study in part reflect our contemporary understanding of the natures of things. When we produce order through our classificatory schemes we reproduce or reflect our fundamental understandings of the structure of knowledge. Temporal ordering schemes can therefore allow archaeologists to suggest new patterns and potential causal relationships, but they also structure how we think about past societies and how we can talk about or describe past societies.

One of the most fundamental developments in archaeological thinking was the formalization of the Three Age System. This is an Old World scheme for organizing taxonomically artifacts by their material properties, and using this order as a proxy for the passage of time. Such schemes have old antecedents: for example, in the ideas of Lucretius about the development of human societies over time. The Three Age System represented an important development in nineteenth-century thinking and organization of archaeological material into Stone, Bronze, and Iron Ages (Gräslund 1987). Formalized by C. J. Thomsen in his role at the Museum of National Antiquities, Copenhagen, the scheme quickly led to the development of chronologically defined subdivisions by scholars such as J. J. A. Worsaae in Denmark and John Lubbock in Britain. With the development of these schemes came the bones for all subsequent archaeological studies, which have latent at their hearts themes of linear, directional, or teleological sequences or development over time. These approaches also saw the beginnings of a continuing concern among archaeologists to deriving increasingly well-ordered and precise chronologies.

If the formalization of the Three Age System in the nineteenth century provided the background for archaeological thought, it was a pioneer of early-twentieth-century archaeological thought who took these schemes to their most developed fruition. V. G. Childe's work organizing the culture historic model of European prehistory provided the intellectual framework for modern archaeological approaches. Culture history

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schemes approach assemblages of material as indicative of the presence of groups of people defined as archaeological cultures. Variation within these groups is glossed over within cultural “blocks” which are delineated in space *and* time. Childe’s strengths lay in his ability to synthesize and organize large volumes of evidence from wide areas of Europe. His culture history tables provided essential clarity and order in studies of prehistories where, prior to the advent of scientific dating, typologies (associated with other contextual information) were the only ways of providing a narrative structure.

As a means of domesticating and organizing the past, these approaches are invaluable, but they are also limiting. The time dimension in these approaches takes on a series of very specific qualities. First, as identified as monolithic units, the potential for change in archaeological cultures seems difficult, and archaeological cultures become seen as static. Second, the ordering—the sequence of things in the time dimension—predetermines how things happened in “the past.” Third, because these schemes are defined by our contemporary understanding of the nature of things, they say much more about contemporary knowledge systems than necessarily changes in material culture over time, or previous knowledge systems. Culture history approaches emphasized critical differences between assemblages, and this left it open to bias and subjectivity in the treatment of the schemes. This was not simply in terms of which traits in cultures were the most important to record, but also they structured the fundamental organization of these schemes. An example will demonstrate how situated these systems are. When Childe was developing his culture history schemes of northern Europe, it was received truth that European cultures always developed out of “Near-Eastern” ones. In part this approach derived from the model of change employed in culture history narratives; typology determined that traits or types of materials developed one from the other. Traits could therefore be tracked as they diffused from the point of origin outwards. Childe at one point developed two schemes for European prehistory, but adopted one which positioned the European Neolithic megaliths after the Near-Eastern one *because* of this universal relative truth. It was not until the development of radiocarbon dating that

a model of diffusion *ex oriente* was demonstrated to be incorrect. With synthesis and organization came the tendency to draw lines through the aspects of the culture history schemes with most ambiguity. A corollary of this is that the differentiation between abstract taxonomic “blocks” of culture has quite a specific set of implications for temporal change in narrative structures (see below).

Developments in excavation approaches often occurred in the form of more sophisticated ways of documenting physical proxies, which on archaeological sites stand in lieu of the passage of time. Thus, Mortimer Wheeler’s grid system provided spatial control in plan, and multiple samples of the vertical nature of deposits which stand for change over time. The Harris Matrix approach to recording was developed to schematically represent archaeologically observed relationships among the different deposits, negative features, and structures which provide spatially defined analogs for the passage of time. Single-context recording systems employed in British archaeology seek increasingly accurate and sophisticated representations of observed physical phenomena on the ground as a means to document things that stand for the passage of time.

While all these approaches attempt to document more accurately observed phenomena, all are highly speculative and situated, as Ian Hodder’s famously observed interpretation begins, at the trowel edge. All of these approaches attempt to document in the production of the written, drawn and photographed archaeological record evidence which we can equate to processes that occur over the passage of time (Patrik 1985). As such, space on site becomes the means of documenting evidence for the passage of time; as with the physical properties in artifactual culture history typologies, space now becomes analogous for time then. Attempting to understand the problematic timescale returns in many cases to models that use spatial characteristics to distribute order, and this process is problematic. While doing so, spatial models often abstract representations of time, so that site phase plans reduce activity (the “Iron Age”) to a two-dimensional, spatially defined model. The use of such visual iconic analogs—as David Clarke termed them in his 1973 book *Models in Archaeology*—does much to flatten the interpretation of activity that might have

occurred over various different durations, with obvious implications for our narrative structures.

A tendency to flatten and abstract time on individual sites is arguably compounded by a continued reliance on period-defined, sequential, culture historic models. Culture history models maintain an importance in archaeological narratives to varying degrees in different parts of the world, but they are also the latent narrative structure in any archaeological discussion that employs these terms as proper nouns; if you excavate on a site and you are looking for the “Bronze Age,” you are excavating within a culture historic scheme, with all the potential for contemporary narrative bias as Childe’s model of north European megaliths post-dating those in the eastern Mediterranean. These culture historic approaches are incredibly pervasive, despite the clear problems with the normative idea that groups of material culture can be equated with specific groups of people, and the problems of envisaging culture defined spatially with an absence of change, diversity, and variability. They remain the basis for archaeological temporal thought decades after the realization that these models were problematic (Thomas 1996, 97), even in areas where archaeological theory has called for more sophisticated approaches as part of a material-turn in intellectual thought.

A further issue can exist in terms of attempting to identify patterns in material culture over space and time that are indicative of previous peoples’ choices and behaviors. In many regions, a tendency for a culture historic approach to material culture (identifying things as indicative of a set of behaviors associated with a group of people) is compounded by a chronological definition for the lifeways under discussion. In Britain, for example, “the Neolithic” (defined as a suite of material culture and practices) is often defined as beginning at a calendar point in time. Here we see a conflation of what archaeologists should be investigating (patterns in material culture over space and time) with the scales along which we organize our evidence (specific points in time; the spatial unit of analysis). The archaeological concept of the culture has here become a thing itself, and the evidence for the systems that we should be using to organize it mean that archaeologists very obviously risk structuring their causal

narratives with their contemporary epistemologies. This is a logical fallacy; defining culture by a time unit and/or an archaeological concept will predetermine our narratives (Griffiths 2017).

This tension between the subject of archaeological enquiry (different distributions of material culture defined in space and by proxies for time) and the normative culture historic categories we employ is a conceptual tension, not a clash of chronological systems (Lucas 2005, 9; cf. Griffiths 2017). Among many contemporary archaeologists there is an assumption that periodization more or less remains empty of its original narrative content and is largely a relative chronology devoid of specific meaning (Lucas 2005, 50). For a discipline that has strong emphasis on ways of observing the passage of time, our lack of attention to the structuring role of chronology in our narratives is perhaps surprising. One of the few archaeologists to recognize the inherent issues with these temporal tensions is Ann Ramenofsky (1998).

Ramenofsky (1998) emphasized the importance of differentiating time, the units of measurement of time, and the structuring model organizing these units; it is always essential to regard chronology as a conceptual, imposed model of evidence for the passage of time. Many of the underlying causal narratives that are invoked in archaeology could derive from inaccuracy in the orderings of chronologies, or in terms of chronological imprecision being mistaken for correlation. Ramenofsky differentiates between ordinal (e.g., culture history-inspired periodizations) and interval (e.g., radiocarbon years) temporal data. The tensions between narratives that are played out using these different schemes but where archaeologists have not understood that they are employing distinct datasets brings to mind Stuart Piggott’s famous appraisal of the then-new radiocarbon measurements from Durrington Walls, which he deemed archaeologically unacceptable. In short, like Childe’s view of the Near-East pre-dating northern European megaliths, or Piggott’s view of the Durrington Walls radiocarbon measurements, ordinal chronological data can be significantly at odds with interval chronological data. Because the mistakes that Childe and Piggott made now look so obvious, and many contemporary archaeologists have access to more interval (radiocarbon

or other scientific) measurements, it would be arrogant in the extreme to believe that we as contemporary archaeologists are inured to such oversights, when many contemporary archaeologists employ as their basic ordering systems culture history-derived ordinal schemes.

A different discussion of the influence of temporal resolution has been espoused by Geoff Bailey with his “time perspectivist” approach. A central theme of this approach has been the importance of the palimpsest, and attempts to unpick the time-depths of different anthropogenic and sedimentological elements that comprise an archaeological site. This approach would argue that the structural temporal properties of the materials that comprise archaeological sites fundamentally limit the kinds of questions that archaeologists should attempt to explore; that the time scale—the perspective—will change the causal mechanisms employed, with some processes only visible on longer and coarser timescales. An additional theme that overlaps with other archaeological approaches to time is that the subjective conception of time is culturally specific (see below).

In contrast to schemes that order and organize the division of time, significant emphasis has been brought to bear by archaeologists on the more experiential properties of time. These have included approaches to portable material culture, sites, or landscapes (for example by Christopher Tilley), including an emphasis on the importance of the past in the past (for example by Richard Bradley) and the importance of perceptions of time in other cultures (e.g., Gell 1992). Much of the archaeological concern with temporality can be traced to the use of the term in the paper published in 1993 by anthropologist Tim Ingold entitled *The Temporality of the Landscape*. The impact of this paper on archaeological writing can be identified by the frequency with which it is cited.

Ingold’s paper takes as his point of departure the discussion of a landscape painting by Pieter Brueghel the Elder, *The Harvesters*. Describing the processes on-going in the image, Ingold attributes temporality to various aspects of the landscape and coins the term *taskscape* to describe his approach. This concept has been highly influential. However, the approach brings us back to the importance of narrative in temporal approaches; arguably, the subjects of the image—continuously

suspended in their existence forever—do not quite successfully achieve a temporality without Ingold as negotiator.

The use of the archaeologist as the narrator or magus to animate the past has produced some evocative archaeologically thick descriptions, especially of landscapes. Temporality is often written of in terms of the experiential quality of material culture, or the enduring or durational qualities of aspects of the archaeological record. Laurent Olivier’s (e.g., 2001) work on this theme emphasizes such things as multitemporality and enduring things, and a continuity with pasts that do not exist, in opposition to “the present,” which Christopher Witmore has described as percolating.

Approaches emphasizing the past in the past have extended to sites, landscapes, and objects—for example, a Neolithic axe in a medieval house floor—and have provided rich themes for archaeological writing. Emphases on the importance of the perception of the passage of time and the importance of different magnitudes of temporality have often been used as ways of *explaining* or adding causal rationale to practices in the past (often with the idea that value is attached to the already old as powerful, magical, or potential with associations with the ancestors, authenticity, and so). These approaches marry into ways of writing about material culture that take an object biographic approach. At the center of these approaches is the idea that things’ natures can accrue and be transformed over their life cycles. Biographies of things include their creation and “life” courses, as well as identities derived from the network of relationships with people and other agents. The temporalities of things are therefore not simply defined in a time-linear manner, but might be understood as the temporal qualities in terms of the worldliness of things.

The realization that temporality has significance leads us to the obvious corollary that temporality will have different significance, symbolism, and symbolic value in different social systems. More anthropologically informed approaches to the temporality of landscape and things have led to considerable interest in the range of ethnographic examples of how time, chronology, and temporal change are marked, represented, and understood (e.g., Gell 1992).

There have been numerous classic anthropological examples that detail these examples, though there is a common stress on the perceived directionality of the passage of time and usually its linear (though frequently the cyclical) career. These studies have stressed that in human terms the experience of time—and especially of time associated with valued or charged social contexts, such as with rites of passage or ceremonies—can have different or special qualities.

Related to the anthropologically informed emphasis on the specificity of time schemes have been archaeological approaches to the political dimensions of time. Perhaps the most optimistic and subtle version of this was work in the 1970s by Mark Leone, which explicitly drew attention to the ways in which contemporary archaeological practice was structured by our temporal understandings, and how other societies might equally be enmeshed in their temporal rationale.

Archaeology as a subject that looks for patterns in the distribution of material culture over space and time, and attempts to analyze these as indicative of previous peoples' choices and behaviors, is wedded to the importance of time as an axis of analysis, and temporality as a means to approach other peoples' worlds.

SEE ALSO: Memory

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Airborne Laser Scanning and Lidar

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Lidar has become a standard tool of the landscape archaeologist, its name being a portmanteau of **light detection and ranging**. In archaeological publications, lidar is commonly used to describe airborne laser scanning (ALS), with terrestrial laser scanning (TLS) normally being referred to as three-dimensional (3D) laser scanning, although both ALS and TLS use similar lidar technologies. For the purposes of this entry, lidar refers to ALS. Lidar was first developed in the 1960s, although simpler devices with similar principles were in use before this date; but it was the 1990s before lidar was first applied to archaeology. The principle of lidar is relatively simple; a pulse of infrared or near-infrared light is fired at the ground from an aircraft. Fixed wing airplanes, helicopters and unmanned aerial vehicles (UAVs) can all be used to carry the lidar sensor. The length of time the pulse takes to reach an object and be reflected back to the sensor is then recorded. Using the speed of light, the distance the pulse has traveled can be calculated. Converting this basic principle into a technique that can be used to provide highly accurate 3D measurements is a little more complicated.

Lidar sensors generate between 20,000 and 100,000 pulses of light each second. These pulses are emitted in a side-to-side sweeping scan as the aircraft travels forward, creating a wedge shaped scanning area beneath the aircraft. This produces a measurement density of between 1 and 20 points per square meter, although the altitude of the aircraft will affect this density. Establishing the position of the aircraft is essential, as the sensor needs to know exactly where it is measuring from, therefore a global navigation satellite system (GNSS) is used to record the position of the sensor multiple times each second. The GNSS

receiver is in constant contact with a number of known points on the ground known as ground stations. To maintain a high level of accuracy, the aircraft needs to remain within 30 km of one or more of these ground stations. A further consideration is the small variations in altitude, pitch and yaw of the aircraft encountered during flight. To correct for these movements the aircraft carries an inertial navigation system (INS), which records these variations. So by combining the speed of light calculation to obtain a distance, the angle the pulse is emitted and the exact position of the aircraft, to establish position, a point cloud is created. This point cloud contains a number of 3D points representing the surface beneath the aircraft.

Complementing the spatial measurements, the sensor can also record additional data including the intensity measurement; this is quite simply the percentage of light that the target surface reflects back to the sensor. Intensity measurements can help to differentiate between different objects being sensed due to their variable reflective properties; this can assist with point classification. It has been demonstrated that subsurface archaeological remains can affect the reflective properties of the overlying vegetation in a way comparable to the formation of crop marks (Dèveux et al. 2005); thus the intensity measurement can be utilized to detect subsurface archaeology. Some sensors are also capable of recording the color of target objects as red, green, blue (RGB) values, so seven measurements can be associated with each point in the cloud:

- x coordinate
- y coordinate
- z coordinate
- intensity
- red
- green
- blue.

A well-acclaimed capability of lidar is its apparent ability to “see through trees”: a facility lacking in comparable techniques like aerial photography or satellite remote sensing (Challis

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et al. 2011). This is achieved by utilizing the fact that when each pulse of light is emitted by the sensor, instead of persisting as a single point of light, it gradually spreads out, similar to the beam of a torch. When the beam reaches the surface it will have a diameter of around 0.1 m if emitted from around 1,000 m. As the light approaches a wooded area, some is reflected by the crown of the canopy and returned to the sensor; this is the first return. Further portions of the light are reflected at various levels within the canopy; these are intermediate returns. A small portion of the light may reach the ground before being reflected; this is the last return (although the ground is not reached in all cases and the last return may occur within the canopy). The phenomenon of multiple returns is what enables lidar to model both the woodland canopy and the ground surface beneath. A surface generated from first returns is a digital surface model (DSM), and one generated from only last returns that have reached the ground is a digital terrain model (DTM).

Unprocessed lidar data are normally available in the industry standard .las or .laz format; this contains a 3D position along with intensity and RGB data for each point. This format contains the first and last returns along with a number of intermediate returns, as determined by the capability of the chosen sensor. In a limited number of cases the entire return profile is recorded: this is called full-waveform lidar. Full-waveform data has the advantage of allowing more control when attempting to separate tree cover from the ground surface, potentially producing better results. Complementing the unprocessed lidar data, pre-processed products are available: these are delivered as raster data in .tiff and .asc formats, in vector format as a .xyz file, or pre-hillshaded images in .jpeg format. They are supplied in both DTM and DSM versions generally as 1 km² or 0.5 km² tiles. The use of pre-processed data allows researchers to bypass the data-processing steps, as it is delivered pre-filtered and pre-rasterized. This allows the project to immediately proceed to the visualization and interrogation of the data, but removes any control over how the data are filtered and converted into a raster.

If unprocessed data are used, it needs converting into an archaeologically useful form. To achieve this, numerous steps need considering,

the specifics of which vary depending on the software package used; therefore the following is a general outline of the process. The initial step is point classification; this is a process by which the multiple returns from each pulse are grouped in a meaningful manner. For archaeological purposes the important group is the “ground” classification. Classification involves the use of algorithms to differentiate ground points from final returns occurring higher in the canopy. Numerous algorithms are available that generally look at a radius of points around the one being analyzed, establishing how they relate. If the point would cause a sharp unnatural change in topography it will be considered a mid-canopy reflection, whereas one at a similar elevation is considered a ground return. Numerous passes are made with these algorithms until a relatively smooth ground surface is achieved. These algorithms have user-definable values so the search radii and the angle considered shape are tailored to suit the wooded area’s terrain; however, over-processing can have the effect of hiding archaeological features.

Once the ground points are identified the processor will have to decide either to retain the data as a vector, or to convert into a raster format; this depends on the end product required from the lidar. If this product involves the presentation of a 3D surface in a virtual environment, then retaining the data in a vector format may be preferable. To achieve this, the ground points need converting into a triangular irregular network (TIN); this process involves joining the points with straight lines, creating a series of triangles. These triangles will be larger in areas with low point density and smaller in high-density areas. The TIN’s advantage is that the file size generated is relatively small compared with that of a comparable raster, and as none of the points are moved, a TIN retains high spatial accuracy. The disadvantage of this method is that the spatial analysis and visualization options are more limited than are available for rasters.

The alternative to the TIN is to convert the point data into raster format, which involves fitting the data into a regular grid; again this involves making a number of decisions that may affect data quality. The resolution of lidar data is normally quoted as points per square meter, but when viewed from above the data

are not evenly distributed. This unevenness is partly caused by the undulations of the Earth's surface, partly by the movement of the aircraft and partly by the number of points filtered out during the classification process. The next stage of the process is to decide what size each cell in the grid should be. The smaller the cell size, the higher the resolution, but this will result in a larger file size. A cell size is normally chosen which is similar to the average spacing of the points, although a larger cell may be chosen if there is a large standard deviation in the point spacing or to reduce file size.

When a grid is imposed on unevenly distributed points it will result in some cells containing multiple points, some containing only one, and others containing none. The next stage in the process is to allocate a numeric value to each cell. To generate a DTM the point's z-value is used; alternatively, for an intensity visualization it will be the i-value. For cells only containing a single point, this process is relatively simple—the value of the point is transferred to the associated cell. However, for cells containing multiple points it is more complicated. For archaeological purposes an averaging approach is generally preferred. This generates a mean average of the points within a cell and assigns this to the cell. Alternative options are available, including choosing the lowest or highest values among others. The mean average approach produces a smoother effect, as unusually high or low values are averaged out, but can result in cells being assigned values which do not match any of the points they contain and can also average out the archaeological details being sought. If a cell is encountered where no point data exists, a value needs to be generated; this can be an arbitrary value that is assigned to all “no data” cells, or an individual value can be tailored for each “no data” cell. This tailoring is achieved through a process called interpolation. Interpolation is a mathematical process that looks at the known values of the surrounding cells and uses these to generate a new value for the “no data” cell. There are a number of different formulae available to

carry out this process, such as kriging, natural neighbor, spline, and inverse distance weighted (IDW); a full explanation of each method is available elsewhere (Wheatley and Gillings 2002, 183). The advantage of interpolation is that a smooth, natural-looking surface is produced without holes in the data; however, this is achieved by adding fabricated values to the dataset. An additional disadvantage of the rasterization process is that it reduces spatial accuracy, assigning a measured value not to a point but to an area.

Once the raster has been generated, a wide range of different visualization options are available, including hillshade, slope and sky-view factor. These can be employed to visualize the data and allow interrogation of the area for archaeological features (see LIDAR DATA VISUALIZATION AND PROCESSING). Alternatively, the raster can also be statistically analyzed in a geographical information system (GIS) to answer a range of archaeological questions.

SEE ALSO: Lidar Data Visualization and Processing; Terrestrial Lidar

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Airborne Remote Sensing

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In archaeology, remote sensing (or Earth observation) is an umbrella term for noninvasive and nondestructive approaches that draw on a range of airborne/satellite sensors for collecting information—in particular, for detecting and understanding sites and landscape without making direct physical contact. This suite of sensors may record buried features and those with a surface expression, and are a primary source for exploring the material traces of past activities and their context, further informed by understanding of both data and landscape processes (ancient and contemporary). In some environments, remotely sensed data provide unique information or offer a step-change in the archaeologist's ability to explore, map, and understand the landscape. Remote sensing approaches embody a development from a traditional focus on sites to examination of context, large areas, and broader processes such as mobility or land use.

Sensors can be characterized as either passive (i.e., imaging) or active, and may be mounted on platforms including satellite, aircraft, and unmanned aerial vehicles (UAV). In passive systems, the sensor (e.g., camera) records naturally emitted and/or reflected radiation (e.g., reflected sunlight), whereas in active systems, a signal (e.g., laser light or radio waves) is emitted and the reflectance or backscatter from the target is measured by the sensor. These basic sensor characteristics interact with the Earth's surface either to provide direct measurement of target attributes (e.g., topography) or to record proxies (e.g., spectral characteristics) through which objects of potential interest are represented. Or they may do both, as with airborne laser scanning (ALS) or light detection and ranging (LiDAR) (see AIRBORNE LASER SCANNING AND LIDAR) where, depending on the wavelength in use, the

intensity of the laser return can provide a proxy for soil moisture and other surface characteristics beyond the topography that is expressed as x, y, and z coordinates.

While some aspects of remotely sensed data may be relatively self-explanatory (e.g., contrast and shadows), other datasets (e.g., hyperspectral imaging and ALS) require extensive data processing and manipulation to produce outputs that support mapping and interpretation (see LIDAR DATA VISUALIZATION AND PROCESSING). These include corrections for uneven surface illumination (radiometric distortion) and variation in terrain, and visualization routines. Furthermore, sensor types and the character of the target area interact with factors such as weather, ground conditions, resolution or scale, bandwidth, and lighting direction to impact on the usefulness of products for particular purposes.

Aerial photography and other passive imaging techniques

Airborne observers taking selective oblique photographs of targets deemed of interest are the original form of archaeological remote sensing (see AERIAL PHOTOGRAPHY). More generally, area-coverage photographs have been used, especially declassified military intelligence imagery and government photography. Historical coverage from the mid-twentieth century and earlier can provide unique records of landscapes that have been comprehensively altered since. For small areas, increasing use is being made of UAVs. Beyond recording the Earth's surface, aerial photographs are used to measure the positions of features and derive three-dimensional (3D) data using photogrammetric techniques. This application has grown as powerful structure from motion (SfM) (see STRUCTURE FROM MOTION) software drawing on developments in computer vision has become readily available and revolutionized the production of point clouds, orthophotographs, and 3D models (see DIGITAL PHOTOGRAMMETRY).

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While traditional photographs record visible light, other parts of the electromagnetic spectrum, such as infrared (see IR THERMOGRAPHY) and thermal imaging, can reveal additional information. Indeed, near-infrared (NIR) has demonstrated its value for imaging vegetation contrasts, and such documentation is especially effective where the thermal properties of archaeological remains have a high contrast to their surroundings. With hyperspectral and multispectral imaging, information from across the electromagnetic spectrum is collected (see SATELLITE HYPERSPECTRAL AND MULTISPECTRAL IMAGING), extending the opportunities for detecting features of interest, such as varying vegetation condition caused by archaeological objects (Doneus et al. 2014).

Active sensors

Active sensors may emit radio waves (radar) or laser energy (ALS), detecting and measuring the radiation reflected from the target to calculate the distance between sensor and target. Such sensors are generally satellite and aircraft mounted, but are increasingly being scaled down for UAVs. They mainly record surface topography, though the sensors also capture information that can be a proxy for buried remains.

The main benefit of synthetic aperture radar (SAR) (see SYNTHETIC APERTURE RADAR) is in providing digital elevation models of large areas, though development of helicopter-mounted systems may provide higher-resolution data more suited to archaeological purposes. Sensor angle can be quite oblique, and shadows created by features like trees and buildings can be problematic. Data can be very noisy, but in some environments SAR records buried features through limited penetration of the surface, and has some capability to penetrate vegetation.

At present, ALS is more developed as a technique to record high-resolution datasets, with ground point densities greater than 25 points per m² routinely available, and UAV-based systems offering in excess of 2,000 points per m². This is a step-change for prospection in woodland if there are enough ground points to effectively strip away above-ground vegetation and so document

subcanopy surface topography. ALS is valuable for slight topographic features in cultivated ground and earthworks, also providing digital surface models for landscapes. In all cases, the point density has a fundamental impact on what is recorded. ALS reflectance values can provide proxies (e.g., varying soil moisture) for buried features such as river channels. The basic approach of laser scanning has been successfully extended to shallow water, through development of airborne laser bathymetry (ALB) (see UNDERWATER THREE-DIMENSIONAL LASER IMAGING) that can record submerged surfaces (Doneus et al. 2013).

Scale and resolution

The usefulness of data for specific purposes will be conditioned by its spatial, spectral, radiometric, and temporal resolutions, and how these inherently connected attributes interact with the character of targets. Spatial resolution in traditional photographs is an expression of the relationships between flying height, camera focal length, and negative size, with the highest resolution offered by large negatives captured from low altitude. In digital cameras and spectral imaging systems, this translates into the size of a pixel as a unit of the ground surface—and the effective ground area of a pixel may vary from less than 1 m² to tens or hundreds of square meters. In optical systems, the quality of the lens will also have an influence on the nominal resolution. This has a fundamental impact on the size of the features that it is realistic to detect. Taking traditional aerial photographs by way of example, these may be captured at scales varying from 1:5,000 to 1:24,000 and beyond. At 1:5,000, a ground feature 5 m across will measure 1 mm across on the image, while at 1:10,000, the same feature will measure 0.5 mm across, and at smaller scales (e.g., 1:100,000) the feature will be vanishingly small. While issues of scale are easily ignored in digital environments where zooming is simple, they none-the-less have major impacts on applicability.

With ALS and other methods of producing digital topographic data, the principal arbiter of scale is ground point density and the pixel dimensions of the surface models produced by processing. For photographs and other imaging, the spectral resolution is determined by

the wavelength width of the different frequency bands recorded, or in the case of radiometric resolution the different intensities of radiation that the sensor can distinguish. Another aspect of resolution is the frequency with which a target area has been documented, and this temporal resolution is fundamental to diachronic studies and mapping landscape or condition change.

Interpretation and mapping

Some applications of archaeological remote sensing have fixated on site discovery, while the output of other remotely sensed data (e.g., digital surface models) has stalled at a stage of producing pretty pictures in which meaning is assumed to be self-evident. To a degree, this is an inevitable consequence of the introduction of novel methods, in the initial stages of which the focus is on resolving technical issues and exploring the character and potential of the data. However, mature applications of remotely sensed data rapidly move beyond this stage to explore what the data tell us about the past. Users of remotely sensed datasets usually incorporate their outputs in geographical information systems (GIS), where they can be combined with other data and used as a basis for interpretation and mapping. It is here that the challenge of moving beyond anomalies and features should be addressed, driven by data articulation and archaeological interpretation. The identification of objects for mapping has traditionally relied heavily on human observers to identify what is of interest. Developments in computer vision and, increasingly, artificial intelligence are being brought to bear in this process. This recognizes that large datasets demand a computational approach, and should exploit the dynamic tension between what a human observer may identify, drawing on experience and knowledge but also constrained by expectation, and what an algorithm may flag in an entirely systematic and unambiguous approach to pattern recognition (Bennett, Cowley, and De Laet 2014) (see SUPERVISED PATTERN RECOGNITION).

Future directions

Since the beginning of this century, we have seen enormous developments in remote sensing, including dramatic increases in availability and resolution of data, and a proliferation of processing routines. These developments present a challenge to better understanding of how archaeological remains are manifested in such data, and how this influences observation and interpretation. Rapidly changing land-use practice, in some cases driven by climate change, is impacting on the continued contribution to knowledge of some approaches that depend on vegetation responses (e.g., photographic/spectral imaging of crop stress), and this is why prospection tools such as large-area geophysical survey are so important. Understanding strengths and weaknesses of methods and their applicability in specific contexts is crucial, without which unthinking applications may lead to disappointment and poorly understood outputs.

Remotely sensed data are central to addressing global inequalities in availability of heritage information. While some countries have benefited from over a century of archaeological inventORIZATION, elsewhere heritage information may be highly localized or nonexistent. The development of rapid methods of large-area documentation, drawing on heavily automated object extraction routines and data analysis, is crucial to addressing these disparities. Not only do such developments move beyond the limited capabilities of human observers to explore large and complex datasets, but also they should place the processes of identifying objects of potential interest on a more explicit and systematic basis than can be achieved by a reliance on traditional observation alone.

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FURTHER READINGS

Archaeological Photography

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Archaeological photography is the visual documentation of cultural landscapes, sites, features, and artifacts either on land or underwater. It is a key pillar of archaeological practice: the method used to record and study the material remains of past human activity. The role of an archaeological photographer is to systematically record cultural landscapes or artifacts; document sites prior to, during, and after excavation; record heritage features and standing structures; photograph the spatial association between artifacts; record archaeological methods for lectures and publications; and archive the archaeological record.

Archaeologists have a responsibility to create a technical and illustrative photographic archive for future generations and often under varying circumstances. The archaeological photographer is challenged by temperature, wind and dust, moisture, difficult terrain, vegetation, and commercial time frames. Typical challenges could be determining which artifacts should be photographed in an assemblage of thousands of objects, dealing with high-contrast site photography, or flash photography of a confined cave excavation. The archaeological photographer must assess what site perspectives or artifact detail should be recorded. The photographer is required to apply different lighting methods and perspectives to a variety of heritage—site features, ceramics, stone artifacts, coins, glass, bone, shell, metal, wood, and textiles. Archaeological images form a scientific, evidential record and should be illuminated correctly, well focused, suitably exposed, and free from distortion. Accurate color representation and the use of a proportionate contrasting metric scale or indicative human figure are important considerations.

From the outset, archaeologists recognized the potential of photography to permanently

record scientific endeavors. Photography enabled a global dissemination of new knowledge of past societies. From large-format cameras and glass plates to single lens reflex (SLR) to drone cameras, archaeologists have constantly sought to use new technologies to capture and document heritage. Given the imperative to systematically document during artifact conservation and excavation—inherently a destructive process—archaeological photography was an ideal, complementary alternative to the drawn record. Maurice Cookson (1954) typified a rigorous, systematic approach to photographic recording and became a key figure in the development of archaeological photography in post-World War II Britain. Technical aspects of archaeological photography were later explored by Harp (1975), the *Deutsches Archäologisches Institut*, and further championed by Dorrell (1996) whose *Photography in Archaeology and Conservation* has become a seminal technical work on the subject. In the tradition of Cookson and Dorrell, the Institute of Archaeology continues to offer archaeological photography as a formal stand-alone subject. Unfortunately, this is still a rare offering at universities globally.

Recent literature on archaeological photography has focused on three-dimensional (3D) case studies rather than on international standards or new approaches to artifact photography. There has been relatively little academic discussion over the last decade concerning standards in archaeological photography, metadata, photography of artifact assemblages, small artifact scanning, and streamlining artifact photography workflows and project archives using digital asset management (DAM). There is potential for greater standardization, including international scales, approaches to technical documentation of artifact types and assemblages, and a greater emphasis on university technical training and accreditation—critical given the exponential increase in digital output. Archaeological images should equal or surpass those of the past.

The relationship between photography and archaeology has come under closer inspection, with an examination of the way the past is

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perceived and the objectivity and subjectivity of cultural images. Visual anthropologists have critiqued the “objective” representations of reality in archaeology to argue for an artistic, even subjective role of the cultural image. Personal camcorders are now used during excavation to personalize archaeological research and demystify the objective nature of archaeological method.

Aerial photography and satellite imagery are extremely useful prospection and analytical tools and have provided a key site and landscape perspective since the advent of the first camera in the 1840s. Low-level aerial archaeology platforms including kites, balloons, and photographic booms enable archaeologists to obtain aesthetic vertical and oblique site images. Given the development of unmanned aerial vehicles (UAVs) by the military, it was inevitable that low-cost drone systems would become available to and adopted by archaeologists.

Scientific photographers employ infrared, near-infrared, ultraviolet (UV), and multispectral imaging techniques to highlight archaeological details difficult to detect in the visible light (Dorrell 1996). Visible light, UV reflectance, UV fluorescence, and infrared photography can be employed to detect chemical signatures indicative of textile colorants (Baldia and Jakes 2007). Other artifacts suitable for multispectral imaging include painted wood, canvas, leather, and the ink on parchment, such as revealed in biblical inscriptions. Fluorescence photography can distinguish the presence of organic and mineral elements in wall-paintings and textiles, and xeroradiography can assist conservators in the restoration of metal artifacts. Archaeologists exploring confined spaces utilize endoscope photography. Scanning electron microscopy (SEM) is a key imaging tool to identify residues and use wear. Laser scanning confocal microscopy (LSCM) and 3D focus variation microscopy (FVM) are being used for use-wear analysis in lithics research.

The greatest change in archaeological photography has been the exponential increase in photographic resolution and uptake of camera hardware, the obsolescence of film emulsion, laser scanning, and drone technology. Given the time, effort, and cost involved in producing archaeological images, high-quality archival records

should be standard. Historically, large-format or medium-format cameras with digital backs were the ideal due to the level of detail extracted from the negative. Archaeologists are closer to this ideal, with 30- to 50-megabyte digital single lens reflex (DSLR) cameras approaching parity with medium-format resolution. The explosion of mid- to high-resolution mobile phone cameras also has provided archaeologists with a snapshot record, albeit with limitations. Handheld, ultra-portable 3D laser scanning cameras may eventually be manufactured to provide greater manipulation of stone artifact conjoins, mosaics, architectural elements, glass, and pottery.

Recent developments in archaeological photography and computational photography include the application of multiple light imaging or polynomial texture mapping (PTM) to site features and artifacts (Duffy et al. 2013). A two-dimensional (2D) process, PTM relies on multiple sources of light from different angles to define variation in the surface of the object or feature. Structure from motion (SfM) is a photogrammetric range imaging technique that enables archaeologists to produce 3D structures from 2D image sequences. High-resolution digital imaging enables the archaeologist to speed up the documentation of endangered sites due to erosion, development, and conflict (CyArk project). Laser scanning allows archaeologists to create virtual monuments and interiors, document excavation stages, and illustrate sites for virtual reality (VR) experiences. Laser scanning and computer-numerical-controlled (CNC) design or large-scale 3D printing could be used to replicate small artifacts or even replace destroyed or stolen elements of buildings.

Computer enhancement of rock art has been utilized for decades to shed light on difficult-to-detect images or recover previously recorded art images. The results can provide additional opportunities for relative dating and a potentially vast corpus of new rock art. Jon Harman developed D-Stretch, a low-cost app to enable the reevaluation of rock art. Advances in mobile computing enable archaeologists to illustrate directly onto rock art imagery and minimize the impact of tracing directly onto the rock art surface.

Digital imaging has provided greater opportunities for archaeologists to store, retrieve, and

disseminate research via image databases or the cloud. The challenge is to ensure authenticity of the original digital image and manage archaeological image workflows when utilizing open source digital asset management (DAM) software. It is foreseeable that medium-format resolution will be available in the size of compact camera and that portable 3D scanning cameras, inbuilt camera scales, and/or metadata inputs linked to DAM workflows are likely to become standard. Archaeological photography is now firmly in the realm of both high-resolution 2D recording and a complementary, immersive 3D, aerial, or VR experience.

SEE ALSO: Archaeological Videography; Authenticity in VRM; Computational Photography; Conservation Documentation; Digital Heritage; Drones; Image-Based 3D Modeling; Imaging in Human Remains; Laser Scanning; Photorealism and Digital Reconstruction; Reflectance Transformation Imaging (RTI) in Conservation; Structure from Motion; Underwater Three-Dimensional Laser Imaging; Virtual Reality Modeling

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Augmented Reality

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Augmented reality (AR) is part of the wider concept known as mixed reality (MR). MR is generally accepted as a way to seamlessly combine our perception of the real world with digital or created elements. It is best defined by a scale known as the reality–virtuality continuum first proposed by Milgram et al. (1995).

As can be seen in Figure 1, the scale goes from the real environment (RE) through AR and augmented virtuality (AV), to a full virtual environment (VE). The full VE can be thought of as virtual reality (VR). The term virtual reality (see VIRTUAL REALITY MODELING) has now been accepted into modern everyday language, and has been defined as the computer-generated simulation of a three-dimensional (3D) image or environment that can be interacted with in a seemingly real or physical way by a person using special electronic equipment, such as a helmet with a screen inside or gloves fitted with sensors. VR involves the entire creation of a world within a digital environment; AR, on the other hand, involves the limited creation of digital elements, which are then combined with the real world.

AR therefore allows a user to work in a real-world environment while visually receiving additional computer-generated or modeled information to support the task at hand. There are a wide number of applications of this technology: interactive greetings cards, advertising of various products, visualization of computer-generated geographic information systems (GIS) data overlaid onto actual locations (Ghadirian and Bishop 2008), and indoor and outdoor gaming; even heads-up displays (HUDs) in modern aircraft are a form of AR—overlying information from the aircraft's systems and projecting them onto the pilot's display.

Visual AR can be deployed using three main methods: a head-mounted display (HMD), a smartphone or tablet, and projection mapping.

- *Head-mounted display (HMD)*: HMD involves the user attaching a device to

their head that mediates what they see; the device can overlay information directly onto a see-through screen, meaning the user is seeing the real world through their own eyes (an optical see-through device, for example Microsoft HoloLens) or through a completely closed system, where the information fed to the eyes is via one or more video screens bringing information from cameras on the outside of the device (a video see-through device, for example Google Daydream).

- *Smartphone/tablet*: By using the built-in sensors (global positioning system (GPS), compass, accelerometer, camera, etc.) of a tablet or smartphone this can provide a relatively low-cost and accessible approach to AR. Typically in this case, the video feed from the on-board camera is augmented with virtual information as the user moves around. This is the most common use of AR, and is quickly becoming popularized through the use of location-based gaming such as Pokémon Go, and social media applications such as Snapchat. AR using user-held or worn devices can be triggered in two main ways: location-based AR and marker-based AR.
 - *Location-based AR*: One of the over-riding concerns when deploying an AR experience is to ensure that the digital content is delivered to the user with the correct perspective and scale and is registered correctly with the real world. For the digital content to be placed accurately in relation to the user, the AR delivery device needs either to have knowledge of the user's current location (via GPS and digital compass) or to be able to interpret what the user is seeing in real-time (via a 3D depth camera), or a combination of the two. Within archaeological contexts, location-based AR is used most often in location-aware audio-guides; for showing directions to different archaeological features in the field; or for providing other contextual media (such as videos or photographs) in situ.
 - *Marker-based AR*: As opposed to location-based AR, marker-based AR relies almost solely on computer vision algorithms to accurately place the virtual content within the delivery device. A

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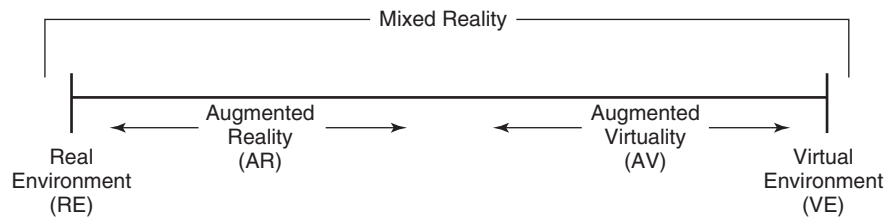


Figure 1 RV scale.

physical, printed marker (such as a poster or interpretation panel) is placed within the real world and, when it is viewed by the AR application, the marker is replaced with digital content. This is often used in museum exhibitions or to augment site signage with extra information.

- *Projection mapping*: Rather than making use of user-held or worn devices, it is possible to project the augmented information directly into the physical space. This method is currently most often used to project images, videos, or animations onto building facades using commercial-grade projectors. The software uses a virtual 3D model to calculate the projection parameters, meaning it is possible to make the projections appear to bend around the building or surface itself. Projection mapping can be used on historic building facades to display the previous phases of a building, or in museum contexts to create interactive exhibits.

Existing example uses of AR in archaeology

One of the earliest applications that used AR for archaeological interpretation is the visual interaction tool for archaeology (VITA) introduced in 2004 by researchers at Columbia University (Benko, Ishak, and Feiner 2004). VITA uses an AR interface to aid in post-excavation analysis of the site of Monte Polizzo. VITA presents a system that allows multimodal engagement with the archaeological data—through use of a head-worn display, a multi-touch projected table surface, speech commands, and a tracked glove. As well as the “world in miniature” mode, where a small-scale virtual model of the excavations is

displayed on the physical table-top in the office, VITA provides a “life-size-world” mode, which shows the textured and meshed model of the excavation at 1:1 scale within the user’s head-worn display. The user’s location is tracked and therefore they can walk “around” the excavation site. By using the tracked glove, users can examine the archaeological finds at their exact locations of discovery within the 3D model. VITA also combines a number of different mechanisms to deal with the various different types of data (two-dimensional (2D), 3D, high-resolution, etc.) which ensures the data are always shown in the most appropriate way; for example, a Harris Matrix is viewed on a 2D display, whereas the 3D model is experienced using the head-worn display.

Applications such as ARCHEOGUIDE (Archeoguide 2010) move the AR experience out of the computer laboratory and into the site itself. ARCHEOGUIDE, released in 2001, is an early example of using an AR device to aid in a tourist’s experience of an archaeological site. When the tour begins, each user is asked to generate a profile outlining what their interests and background are; a personalized tour is then created for that user to follow. The user is given an AR HMD, and reconstructions of the ancient buildings are overlaid directly onto the real world as they walk around the site. George Papagiannakis and Nadia Magnenat-Thalmann (2007) produced one of the best-known heritage AR applications, centered on the site of Pompeii. Using a tracked video-see-through HMD and dynamic modeling of the real and virtual world, Papagiannakis and his team were able to insert virtual characters into various buildings within Pompeii and enact a real-time storytelling scenario, using dynamic occlusion of the virtual objects by both the virtual characters and real visitors. The speech engine in Papagiannakis’s work also allows interaction from

the user—creating a feeling of social interaction with the virtual characters.

Multisensory and multimodal AR

The majority of AR experiences currently concentrate on *visually* augmenting data; however, it should be noted that the other senses can also be augmented: for instance, the use of headphones (such as in an audio guide) or smells introduced into an environment (such as York's Jorvik Centre). The author in his work on the embodied GIS (Eve 2014) uses AR as an exploratory tool, augmenting the results of spatial statistical analysis onto the in-situ landscape of Bodmin Moor, United Kingdom. In addition he makes use of multisensory AR to augment the smells and sounds of the ancient landscape, to enable archaeologists to test hypotheses and change parameters as they are exploring the space. Each sense is augmented in different ways, and some are currently easier than others. For instance, visual and auditory AR can be achieved by HMDs or headphones, but smell, touch, and taste require more sophisticated interfaces—most of which have not yet been used to full effect in archaeological contexts. It should be noted that some of the more successful AR applications (most commonly in a museum context) use a combination of AR interfaces (multimodal) to deliver the experience, adding to the feeling of presence or immersion in the AR content.

Continuing use of AR in archaeology

Currently, AR is in limited use in archaeology. The reasons for this are a combination of the need for specialist programming skills, the cost of the hardware and development of the applications, and the lack of mass adoption of the technology. As with many new technologies, this situation is fluid, and in the coming years both AR and VR technology is due to be widely adopted, with some industry analysts predicting a paradigm shift away from using monitors and keyboards to using HMDs with context- and location-aware content for our primary interaction with computers. As the technology becomes more widespread, there are

clear avenues for the use of AR in archaeology. The main drive currently is for use in education and tourism for museum displays and also for presenting archaeological information to the public on heritage sites, in situ. We can expect this remit to expand in countless different ways, some examples of which may be:

- AR being used to aid in artifact identification (for example, recognizing and recording animal bone species);
- conservation (virtually marking repairs on structures or objects and using an AR viewer to see them);
- augmentation of museum or heritage site literature;
- augmentation of 3D-captured artifacts into public and private spaces (for example, a virtual Greek urn sitting on your shelf at home);
- ongoing archaeological excavations being captured digitally and then displayed in situ after the trenches are closed.

AR can also facilitate the creation of “what-if” scenarios, by providing a platform to create various theoretical models of site-use which could then be tested from a body-centered perspective. For instance, what would a certain landscape have looked like if it was covered with trees? How would the shape of a house change in the landscape if it had a porch or windows? What if the ground level was lowered or the course of a river changed? What if there were other semitemporary buildings built into a settlement, which may have not survived in the archaeological record? What would the landscape look like in varying different weather conditions (bright sun, fog, snow, heavy rain, etc.), and how would this affect the views to and from a specific monument? It is possible to remove modern intrusions in a landscape using AR technology (sometimes called diminished reality), allowing a site manager to virtually remove modern buildings or infrastructure to give an impression of the past landscape.

AR technology is still at an early stage, and while some sophisticated applications can be currently built, the technology is only going to improve, and the future holds many exciting

prospects. AR, working in tandem with advances in 3D reconstruction, means we can now undertake body-centered journeys through our data that were previously in the realm of science fiction and that will now open up new insights and discoveries of our shared past and allow archaeologists and tourists alike to experience the sites and artifacts in new ways.

SEE ALSO: Computer Applications in Archaeology; Digital Heritage; Digital Photogrammetry; Embodiment; Mobile Geographic Information Systems (MGIS)

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Authenticity in VRM

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Authenticity is a very ambivalent term; it can have different connotations depending on discipline, cultural background, and the individual speaker. It is therefore necessary to explore its meanings before its relevance to virtual reality modeling (see VIRTUAL REALITY MODELING) (VRM) can be assessed.

The roots of the word lie in Greek *authéntēs* (*aut* meaning self and *hentēs* meaning doer), that is, the “originator” but also the “murderer.” The term authentic was first used in regard to texts. In medieval Latin, *authenticum* describes an original manuscript, which was written by the person to whom it is attributed, thus differentiating it from the “inauthentic” texts whose authorship is unknown or unverified. The use of the word has nowadays spread well beyond the confines of historical texts and is used in a great number of contexts with a variety of concepts in its wake, ranging from “personal authenticity,” as established by Jean-Jacques Rousseau, to the authenticity of museum exhibits (Saupe 2017).

The concept of authenticity is best defined by looking at its opposite principles. Staying for the moment with the example of the museum exhibits, this would be the forgery, the replica, and the derivative work. The forgery claims to be something that it is not. It aspires through form, material, and other traits to persuade the observer to experience it as a genuine representative of its kind, with the outspoken intent to mislead. Here, the semblance of authenticity is the prime aim; if it can be achieved, then the forgery is successful.

A replica, on the other hand, can be worked just as skillfully as a forgery, but it does not want to deceive the observer regarding its genuineness. Replicas can be useful when originals are unavailable or too fragile for exhibition or even research (e.g., hominin fossils). They do not initially claim authenticity, but they can acquire it if the original

is lost or they are valued as works of art in their own right.

The latter can also be true for derivative work. It depends on whether the product is perceived as enough of a work of art—as in appropriation art—or as a mere copy, whereby the author of the work and the quality of execution, for example, a cheap souvenir, can have a great influence on said perception, and with that on the authenticity of the object.

From this it becomes apparent that two kinds of authenticity are at work: one inherent to the artifact, the other based on (public) discourse. For museum exhibits, the questions appear to be: are they genuine, are they original, are they art? But looking at other disciplines and objects, a much wider range of criteria may be applicable. In heritage preservation, the concept of authenticity has undergone a marked change over the last decades. At the beginning of the twentieth century, authenticity was felt to be located in the extant remains of monuments, whereby it was debatable whether later additions or changes to these monuments also held authenticity or not. In the Test of Authenticity (§9) of 1977 (UNESCO 1977) “design, materials, workmanship and setting” were seen as essential, whereby subsequent additions or changes were also included. That this reflects a rather western, in contrast to a global, approach to authenticity was recognized in subsequent years, leading up to the Nara Document (UNESCO 1994). In §13, the scope of authenticity was significantly widened in order to incorporate non-western concepts. The criteria for authenticity now included “form and design, materials and substance, use and function, traditions and techniques, location and setting, and spirit and feeling, and other internal and external factors.” Including tangible as well as intangible values in the test of authenticity is an appropriate response, especially when dealing with monuments, which undergo continuous alterations—be it for spiritual reasons or from a conservational standpoint. Despite these changes, it can still be argued that authenticity remains a more or less western concept.

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The use of the word *authentic* in the realm of living history (and in part in experimental archaeology (see *EXPERIMENT IN ARCHAEOLOGY*)) encompasses a similarly broad spectrum. Raw materials, modes of work, or designs as gleaned from archaeological finds, together with other characteristics, are often termed *authentic*, leading to contradictory concepts like “*authentic replicas*” (Samida 2014). The strive for authenticity in living history also encompasses the yearning for authentic emotions.

Not only staged events but also memorial places or historical sites vie for our emotions. It is often argued that it is the aura of a place, its material authenticity, that makes us respond to it. On the other hand, the auratic experience could well be a self-fulfilling prophecy: the claim that a place or an object is authentic and this authenticity lies within its fabric makes us experience it thus (Fitzenreiter 2014). This means that authenticity can be assigned. A pact of authenticity is forged between the visitors and the experts or institutions responsible for the exhibitions in museums and historical sites and it holds as long as the social and cultural context is stable (Saupe 2017). The presentation of the artifacts is staged: they are taken out of their context, artificially illuminated, and presented as something extraordinary. By accepting this view and emotionally responding to it, the observer is agreeing to the pact. Nevertheless, it is not only the artifact that benefits from authentication, but also the authenticator who legitimates his own expertise through the act (Bendix 1997, 7). Accepting that authenticity is a construct, it follows that authenticity can also be deconstructed, for example, when a forgery is exposed.

There has been some doubt whether authenticity (when seen as a construct by experts, institutions, and the general discourse) is actually a useful or even valid concept for the social sciences, especially if it is more or less arbitrarily used to separate what is worth studying, preserving, or exhibiting from what is not (Bendix 1997, 4–9; Seidenspinner 2008, 282).

However, a persistent desire for authenticity can be traced from the mid-eighteenth century up to the postmodern era, in which people long for the real and the true in a world, which is perceived to be full of surrogates and fakes (Seidenspinner 2008, 282).

After considering these in part conflicting definitions of authenticity, it is time to consider how virtual reality models fit into the picture. The models can be constructed in a number of ways; for example, they can be acquired via laser scanner (see *LASER SCANNING*) or they can be modeled by digitizing old paper plans and drawings by hand. The important part is that they are always *constructed*, which means that at some point in their making, subjective decisions have to be taken. No amount of detail can counter the fact that the virtual model is not the real object, but often enough just a hull, which replicates the outer appearance of the modeled artifact. There are methods to capture the interior of an artifact too—a computed tomography (see *COMPUTED TOMOGRAPHY*) (CT) scan may be a case in point—but there are still the questions of resolution and interpretation (see *INTERPRETATION*) of the data obtained from the scan. Therefore, the resulting models are not objective, and interpretations are usually considered to be inauthentic.

Even when looking at certain aspects of VRM—in accordance with the criteria for heritage preservation—namely materials and substance, traditions and techniques, location and setting, use and function, spirit and feeling, and form and design, we find the virtual models lacking. Most obviously, this pertains to materials and substance because we are dealing with virtual and not real artifacts. Traditions and techniques seem similarly inapplicable: the “tradition” of creating virtual models only reaches back to the early 1980s, and the techniques to generate them are ever changing with the advancement of technology. Virtual models, for instance, in the form of augmented reality (see *AUGMENTED REALITY*), can be georeferenced and projected onto a physical site, so that they seem to be located in their “authentic” setting. Nevertheless, this is an illusion, because the model is in itself not bound to a specific place. It is also possible to simulate the use of a virtual model, for example, the workings of a pump, but the way in which we interact with the model is far removed from using a real pump or its functionality of drawing water. Models can evoke feelings, and they can be awe-inspiring and moving, as well as creating a great range of other emotions. This kind of emotional response is often due to staging, for

instance, the play of simulated sunlight through virtual stained glass windows; it is a calculated product conjured up by the makers of the model and not due to its “authenticity.” Additionally, (so far) no real embodiment (see BODIES AND EMBODIMENT) can be achieved, which is vital for experiencing a place with all the senses and giving the *impression* of really being present. Finally, form and design have to be considered. The VRM can delineate the shape of an original artifact in great detail, but what the computer stores is not a real form; instead it deals with coordinates in space and/or mathematical functions which appropriate the form but are not the form in itself. It is possible to create a tangible object from the data, for example, via 3D printing (see THREE-DIMENSIONAL (3D) PRINTING AND ADDITIVE MANUFACTURING); nevertheless, this object would be a mere replica and therefore hold no authenticity. The case may be argued slightly differently for the design of an artifact, if design is considered to be the *idea* behind a shape—like an artist’s vision seen in contrast to the resultant work of art. The intangible vision can take shape in a number of ways, for instance in drawings, physical models, and not least the artifact itself. It could also be represented in a virtual model, as is nowadays frequently the case in architectural planning. In this instance, the model could claim authenticity.

If we accept that authenticity is not an inherent property of an artifact, but something that is assigned by experts, institutions, and the general public, then virtual reality models can also be authentic. In this case, the authenticity would be attributed to the model itself and would not be derived from the original artifact, which has been captured. For this to happen, the model would have to be accepted as an original work, need to be culturally embedded, and be viewed as a product of its time.

SEE ALSO: Geometric Modeling; Heritage: Nonwestern Understandings; Material Culture; Re-Enactment and Engagement

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Computational Photography

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Modern imaging solutions through hardware and software parameters make capturing color, texture, and shape more achievable, and allow for data to be presented in a meaningful way. Computational photography, through a combination of several sensing and algorithmic techniques, extends the options available within digital photography. The resultant data provide an image similar to those captured through standard photography, but one that would not have been possible with a traditional camera. Within archaeology, the use of these different computational techniques depends on the research question asked, but can be broadly categorized as providing image enhancement and restoration, image manipulation through warping and mosaicing, and dynamic range map editing. It should be noted that software and computing power is an essential element of computational photography; without specified software we would be unable to produce and manipulate the data that are produced. The majority of software packages require a graphics system that is able to produce these data. With the ever-increasing file size and pixel resolution of modern digital cameras, the need for more powerful graphic interfaces is essential.

The process of capturing computational photographs is not restricted to a digital photographic camera but can be applied to all aspects of digital medium, including X-ray tomography (see *X-RAY TOMOGRAPHY*) and computed tomography (see *COMPUTED TOMOGRAPHY*) via volumetric image analysis. The development of computational photography is based on the application of digital photography which follows the same techniques used in film-based photography, through a shutter optical device. Digital cameras provide readings of the intensity and color via

light-sensitive receptors known as photosites to each pixel of the image (Corke 2011, 229). The pixel information generated contains color wavelengths through red, blue and green filters to create the interpolated final image. Through their capture, sharpening algorithms are used to emphasize edges; image colors and contrasts are balanced; and the data are compressed to provide a suitable storage system (Adams et al. 2012, 124–126). Computational photography is engrained in the image-capturing process and is not simply completed through post-editing alone. The digital cameras that are currently available no longer take a picture, but instead create one.

The capture of photographs relies on the control of the shutter speed and aperture used. Using too wide an aperture provides light but reduces the depth of field; a narrow aperture gives this depth of field but limits the light available. In archaeology the ambient conditions are hard to control and manage: we are reliant on computational methods to correct these issues through post-editing. A number of different processes can be used, but the general application of computational photography can be seen in image correction through the control of white balance, color, and exposure values. Images are normally captured in a RAW format and are controlled via the operating system of the camera used; these RAW formats contain extensive sources of information due to their uncompressed nature. Errors in light, focus, and motion blur can be corrected through post-editing and the images are converted to suitable compressed file formats, such as JPEG, TIFF, or PNG. These images can be further compressed through a system of pyramid imaging. Pyramid imaging provides multiscale representations whereby they are subjected to smoothing and subsampling, creating a system that allows viewers to use the data based on the computational power available (Burt 2013). This is useful when working with large datasets and can be completed via Gaussian or Laplacian algorithms. Pyramid imaging is beneficial when dealing with large datasets through online

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viewing systems such as IIPImage, as the method allows for examination without the need for direct access to data-intensive files.

The basic elements of photographs can be changed through the computational processes outlined above, but a greater number of resources are available, which can aid archaeological work and vary depending on the purpose of the work necessary. The more advanced computational methods are normally in the form of high dynamic range and tone mapping processes; multiperspective and panoramic stitching; light field imaging; and photorealistic and nonphotorealistic rendering. Photographs captured under normal lighting conditions struggle to show both light and dark areas, with one needing to be overexposed and the other underexposed. High dynamic range (HDR) offers greater control over these exposure values by capturing different levels of exposure. Capturing bracketed images at different steps of exposure allows for the creation of seamless images whereby the different dynamic ranges of luminosity can be combined to bring details out in both the shadows and highlights (Wheatley 2011, 258). This is useful when capturing dark areas such as excavation trenches that contain shadows, or interiors that have external lighting. The ability to control the dynamic range within these images creates a system that is more factual; some digital cameras now implement HDR directly within the capturing process, but the results are better represented through software-based modifications.

Multiperspective and panoramic stitching provides a solution to combine a number of different photos as one representative view. The method relies on a mosaicing photographic capture, where a number of zoomed-in images of an object, site, or landscape are taken and then combined to create a unified image (Gledhill et al. 2003, 436–438). Multiperspective panoramas provide an opportunity to view an archaeological site or object as one complete image which removes issues of perspective and are used extensively within cartography to process aerial images (see AERIAL PHOTOGRAPHY). The process involves capturing a number of overlapping images that are fixed on a single plane. Unlike structure from motion (see STRUCTURE FROM MOTION), angled images are not necessary

to create a result; rather the process relies on a stereophotogrammetry process to create a final dataset that represents an undistorted area. This is beneficial when capturing data that are wide or have data blocking specific elements. Panoramic imaging, however, is generally completed from a single point and combines a series of photographs taken with a sideways and up and down movement. The resultant panoramic dataset generally contains some form of error through the perspective present from the single point of view, but this is countered through the different projection settings available. Different projections are available depending on the use of the images; for landscape-based images, for online distribution in systems such as Google Earth, distortion can be included to produce a complete virtual view and experience. If the data are to be used for metric survey or diagnostic exercises, little to no distortion is required. Through orthographic projections, all levels of distortion are removed and the final image allows for a whole view of a given object, site, or landscape. This is completed through morphing and warping the original images to centrally fit the necessary view; through this manipulation, errors may be present on the extremities of the data. The capture process is important in producing orthographic content, as if the viewpoint is not central, or the surrounding images are not captured, it can limit the extents that can be used. These data can now be shared online, making extremely high pixel images available to those that cannot access the areas, creating greater resources to work from.

Light exists and is identified through the electromagnetic spectrum. What we can identify through our eyesight is known as visible light. The electromagnetic spectrum contains radio waves, microwaves, infrared (IR), visible light, ultraviolet (UV), X-rays, and gamma-rays. Through different camera systems and technology these data can be recorded for use within archaeology and are processed through computational means. Typically, the data that are used within archaeology incorporate IR, UV, and X-ray wavelengths. These provide different systems and tools of identification, with chemical analysis, layering, and thermal and internal properties being available. The different wavelengths are processed as computational images that are modified to fit within

our visible spectral range through a number of different processing options. Attached to differing light wavelengths is the manipulation of visible light color bands such as DStretch (Harman 2005). DStretch works through a decorrelation stretch of an image hue modifying color spaces in specific and controlled ways through defined algorithms; the method is of great use within rock art analysis and allows for nearly invisible details to be enhanced.

The use of computational photography ties in with virtual reality modeling (see VIRTUAL REALITY MODELING) through the production of photorealistic models. The details shown are completed through a series of computational methods that involve the direct manipulation of photographs and textural detail. These provide realistic representations of the past through simplified models and are used greatly within virtual reality. The textures present are processed using computational photography software and then mapped to set features. Each element and face of a model relies on these textures to present the data; without this process, the models created would be represented as simple shaded objects that are unrepresentative of the data shown. Connected to the photorealistic element of virtual reality are the computational processes of nonphotorealistic rendering. This technique provides final images that are similar to drawings, diagrams, or paintings. They are produced through an automatic process where features are detected and emphasized to give simple three-dimensional structures that are defined by edges. Color is sometimes confusing and archaeologists rely on simplified drawings to represent the data shown (computer-aided design (CAD) drawings). Through nonphotorealistic rendering, the method provides a system that removes textural data and is useful within archaeology to highlight areas of importance, or to identify features that may not be as prominent. These can be controlled and processed through a number of different software programs, which offer varying degrees of user control over the data produced.

Although computational photography can be utilized within standard imaging, the method has developed into one that provides three-dimensional spatial data. Systems such as photogrammetry (see PHOTOGRAMMETRY AND

STEREOPHOTOGRAMMETRY), and its digital counterpart, structure from motion (see STRUCTURE FROM MOTION), take these two-dimensional images and process them through a number of different algorithms to create virtual replicas. Photogrammetry has existed since the early days of cartography, but with the application of digital photographs and computational methods, the method now provides a routine means to create usable metric data. As the data are digital they can be manipulated and depth values can be extracted. With the increase in photogrammetric software and image resolution, the results produced can be seen to be similar to laser scanning (see LASER SCANNING) and provide an economical tool for conservation and archaeological recording. Similarly, the image processing, through computed tomography, which is completed via several layered, angled X-ray images, enables a recording method that can identify internal properties. Computational photography is no longer restricted to two-dimensional representations, but now enables novel and metric examinations of archaeologically important artifacts (Miles et al. 2016).

Computational photography can also be utilized to analyze surface details of objects, namely through the reflectance transformation imaging (RTI). The application of taking multiple images with varying light positions enables a two-and-a-half-dimensional examination, where the normal variance of the images is inspected. RTI, through various rendering modes, allows for details to be shown that cannot be seen with the naked eye. The process involves the movement of a virtual light within specific software to introduce shadowing. The method highlights the importance that digital imaging has and how computational photography can increase the results shown. There has been an increase in the use of RTI within archaeological research, involving IR, UV, gigapixel, virtual, and underwater-capture procedures; using standard photography, such results are not possible (Archaeological Computing Research Group 2016).

Computational photography is not just one method; it is a combination of many different computational processes that are used within archaeology. The methods discussed have highlighted a small number of possible processes

available with computer vision and have demonstrated how computer scientists are creating new forms of tools to analyze the past. The method in its basic function provides a means to manipulate the original captured data, but it can be used at varying levels to enhance details in the archaeological record, from simple exposure settings, to dynamic range variations, through to the production of three-dimensional metric data.

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Computed Tomography

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X-ray analysis is used extensively in analyzing archaeological artifacts (see X-RADIOGRAPHY AND CERAMICS; X-RAY RADIOGRAPHY AND MATERIAL ANALYSIS; X-RAY ABSORPTION SPECTROSCOPY (XAS, EXAFS, XANES); X-RAY PHOTOELECTRON SPECTROSCOPY (XPS); X-RAY RADIOGRAPHY; X-RAY TOMOGRAPHY; XRD AND MATERIALS ANALYSIS; and X-RAY FLUORESCENCE SPECTROMETRY (XRF)). X-ray computed tomography (X-ray CT) is a means of seeing inside objects and materials without the need for any destructive intervention. CT scanners are mostly used in medicine, where cross-sectional X-ray images and three-dimensional (3D) reconstructions are used to look inside a patient without the need for exploratory surgery. However, CT is also used extensively in archaeology, where the X-ray images can reveal details of the internal structure and composition of historic artifacts. An issue with the use of X-rays in medicine is that X-rays are ionizing; that is, they have enough energy to eject electrons from atoms, causing damaging chemical reactions in cells. Clearly, in archaeology the adverse biological effects of X-rays are not an issue. The analysis of inanimate objects using X-rays is a form of nondestructive testing.

The word *tomography* is derived from two Greek words—*tomo* and *graphia*. *Tomo* means to cut—as in a *microtome* that cuts slithers of material for examination under a microscope. *Graphia* means to write or draw—so, putting these two words together, a tomogram is a cross-sectional image of an object. For example, a tomogram is able to reveal details within an object unobtainable from an ordinary flat or plain X-ray. In a plain X-ray, it is known that the heart and lungs are inside the ribcage. However, if the ribcage contained a foreign object, the depth of the object beneath the surface would not be apparent. In the case of a plain X-ray of an Egyptian mummy,

for example, it might not be obvious whether an amulet is inside or outside the bandages wrapped around the mummy. An X-ray CT scan will easily show which is the case.

Another major advantage of CT scans over plain X-rays is the dramatic improvement in contrast. Image contrast is a measure of the difference between dark and light areas in an image. The greater the contrast, the easier it is to visually differentiate features. To give an everyday example, it is easier to see objects in bright rather than dim light. A subtle feature might be invisible on a plain X-ray due to lack of contrast with the surroundings but seen clearly on a CT scan.

How are X-ray CT scans produced? Before answering this question, we need to step back and consider the nature of X-rays. X-rays are part of the *electromagnetic spectrum*. X-rays are essentially the same as light rays, microwaves, and radio waves. The only difference is that X-rays have a much shorter wavelength than the former. The shortness of the wavelength means they have greater energy. In an X-ray machine, X-rays are produced by bombarding a tungsten target with high-speed electrons. Electrons are produced by running an electric current through a thin wire called a filament until it glows with an orange heat. This 'boils' off electrons, which are accelerated towards the target using a high voltage (about 125,000 volts in the case of an X-ray CT machine). The high voltage acts like a catapult on the electrons.

The electrons race towards the target at over half the speed of light and when they enter the target they interact with atomic nuclei and produce X-rays. As the high-speed electrons career around the nucleus of an atom, like a racing car on the curved section of a race track, they emit X-rays at a certain angle to the direction of travel—the angle being dependent on the energy of the electrons. As the electrons curve around the nucleus, kinetic energy is converted into X-rays and as a result the electrons slow. However, the process is very inefficient—only about 1 percent of the kinetic energy of the electrons is converted into X-rays; the rest is heat. In practice, the X-rays

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come from a small point on the target and travel at the speed of light to the object being imaged.

When X-rays enter an object, they interact with atomic electrons and are removed from the primary beam. As X-rays penetrate deeper into matter, they are progressively removed from the primary beam through scattering. In other words, the intensity of the beam reduces. This is a bit like throwing a hundred tennis balls into a forest. If we were to go into the forest and measure the distance of each ball from the edge, we would discover that the number of balls would decrease with distance. So it is with X-rays entering an object. The intensity of an X-ray beam entering an object reduces exponentially; that is, the intensity

of the beam is reduced by a constant fraction for each unit depth of penetration.

The X-rays that make it all the way through the object impinge on a detector—in the past film, but nowadays electronic—similar to the detector in a digital camera except with a sheet of material in front of the electronic sensor to convert X-rays into flashes of light—a process known as *scintillation*. If the X-rays have passed through a denser region of a given object, more will be absorbed and fewer X-ray photons will reach the detector. In essence, the denser regions of an object create X-ray shadows.

In an X-ray CT scanner, several plain X-rays are taken from different positions around the

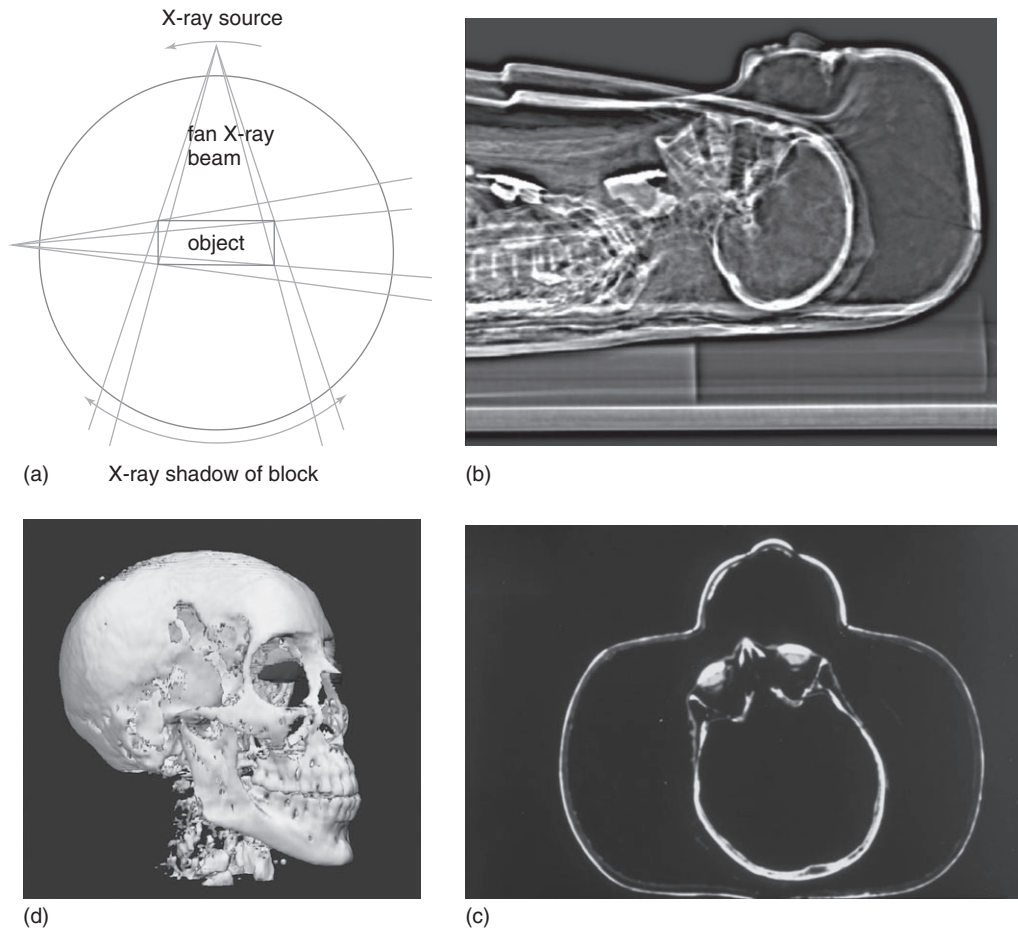


Figure 1 (a) Schematic diagram showing the principles of back projection using a fan X-ray beam projected through an object. (b) Lateral plain X-ray of an ancient Egyptian mummy. (c) Cross-sectional CT scan through head of mummy in (b). (d) 3D reconstruction of skull of an ancient Egyptian mummy.

object to generate a cross-sectional image—think of the X-ray beam seeing around corners. There are many different generations of CT scanners; to illustrate the basic principle, we will use the example of a fourth-generation scanner in which an X-ray tube is rotated around an object, as shown in Figure 1. The main difference between the different generations of device is the speed of image acquisition and image quality. In principle, any type can be used for archaeology, the main limitation being the diameter of the aperture.

For any given position of the X-ray tube, a one-dimensional shadow is produced. A mathematical technique called *filtered back projection* is used to convert the multiple shadows into a two-dimensional (2D) image.

The basic concept of back projection is shown in Figure 1. In this case, we have two line shadows of a rectangle. When the corners on the shadows are projected back to the point source of the X-rays they intersect at the position of the corners in 2D space. Although the mathematical technique is in reality far more complex, the end result is the same.

Back projections produce a matrix of numbers, with each number representing the electron density of the material at each location within the object. The back projection method is like a mathematical crossword puzzle. In a conventional crossword puzzle the words in the rows are consistent with the words in the columns. A computer is used to sum the shadows from different directions to produce a 2D array of numbers. These are manipulated to arrive at the unique matrix of numbers, which is the X-ray CT image.

X-ray CT scanners can acquire a sequence of images through an object with a certain slice thickness and slice separation. For example, a sequence of 100 images could be obtained with 4-mm-thick slices spaced 4 mm apart. In this case, the cross-sectional X-ray slices are contiguous—like the slices in a cut loaf of bread. In the same way that a loaf of bread can be thin or thick cut, the thickness of the X-ray slices can be varied. However, unlike a loaf of bread, the X-ray slices can have gaps between them, so, for example, a sequence of 2-mm-thick X-ray slices could be acquired with a 10-mm separation.

Each image pixel has an area and depth and therefore has a volume. This gives rise to the name

voxel, which is short for *volume pixel* (Michael 2001). The value of collecting a sequence of 2D images is that the data can be converted into a 3D image. One method is to cast rays through the block of data to produce a volume rendering of the object. Another method is to extract a surface from voxels of a certain value—like a contour line on a map except in 3D. Examples of a plain X-ray, X-ray CT scan, and 3D reconstruction are shown in Figure 1. The generation of X-ray CT images would not be possible without the use of powerful computers. The development of X-ray CT scanning was paralleled by the development of mini computers, that is, computers small enough to be placed in the same room as a CT scanner.

This discussion has, by necessity, focused upon the generalities of the technique rather than details. Fortunately, there are a number of volumes that describe the underlying physics and mathematics in depth and detail. However, it should be stressed that the majority of books and scientific papers are about medical X-ray CT scanners, since this is by far the greatest use of the technology. Most archaeology scans, especially mummies, are performed using a medical scanner out of hours or an industrial scanner. Some specialist X-ray CT scanning centers exist around the world, for example the μ -VIS X-ray Imaging Centre at the University of Southampton, UK, has a general-purpose industrial X-ray CT scanner also used for archaeology projects and, for example, has been used to scan Roman coins in pots.

One of the main uses of X-ray CT scans in archaeology is the scanning of Egyptian (Hughes, Wright, and Barry 2005) and Peruvian (Applboom and Stuyven 1999) mummies, clay tablets (Applbaum and Applbaum 2005), wood (Stelzner and Million 2015), and soil blocks (Alessandro et al. 2015). An example from an X-ray CT examination of a twenty-second-dynasty Egyptian mummy from the British Museum, London is shown in Figure 1(b–d). The X-ray CT scan was performed at St Thomas' Hospital, London (Hughes 2011) and a sequence of CT scans was used to generate 3D images of the mummy's head and other parts of the body. The CT scans complemented plain X-rays taken in the 1960s and elucidated details of the embalming process. For example, it was ascertained that the brain was removed through the nose rather than

the foramen magnum. A 3D reconstruction of the skull was generated in order to furnish a facial reconstruction.

SEE ALSO: Clay Tablets; Computer Applications in Archaeology; Cranial Shaping; Craniometry; Embalming; Estimating Subadult Age; Dental Development and Eruption; Image-Based 3D Modeling; Imaging; Imaging in Human Remains; Three-Dimensional (3D) Facial Reconstruction

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Computer-Assisted Restoration

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Digital technology is changing the way we approach heritage preservation. The digitization of paintings, sculptures, architectural forms, early books, manuscripts, and archaeological evidence can provide scholars with new ways of looking at, discussing, and sharing these valuable objects and sites. An important application of digitization is within the field of computer-assisted—“virtual” or “digital”—restoration, a methodology that seeks to question the original appearance of a work of art or site without the need for physical intervention. In digital restoration, diverse forms of high-resolution data can be integrated with conservation records, philological notations, and historical source material using both image-processing and three-dimensional (3D) editing software, thereby addressing the idea of the “original object” by treating originality as a process that changes over time. If conservation is the “management of change,” digital restoration allows us to study that change and understand the reasons an object looks as it does. This is leading to a renegotiation of the relationship between originality and authenticity: There are times when the digitally restored object may be the more authentic, more complete, and more easily understood than a heavily restored and transformed original.

An important aspect of digital restoration is that it allows restorers to rethink physical interventions and follow more cautious approaches when considering their course of action. They can test various propositions before a physical intervention is carried out on the original itself. The high-resolution composite photography and 3D data needed for digital restoration helps to inform decisions and actions. Historians and archaeologists can also employ computer-assisted restoration to visualize theories and investigate

hypotheses about the original appearance and meaning of a work of art. The role of physical facsimiles in the field of digital restoration is changing the way objects are cared for—from their reinstallation in the original location to the reunification of objects separated for different reasons, the emphasis is moving away from the aesthetic display of discrete objects (and fragments of objects) to the awareness that all objects are embedded “things” with a career that reveals not only their original importance but also how they have been valued, appreciated, and understood at different times and in different places. By revealing the changing nature of originality and the decisions that are made during the restoration process, the general public is able to participate in the protection and preservation of the articulate evidence of the past. This approach is bringing art, science, and technology together in the quest for deeper understanding.

A significant role of high-resolution digital archives is in monitoring the condition of an object over time. They are objective records that document the condition of an object at a specific moment in time. This digital information can facilitate a detailed study of the original in case of accident, theft, natural disaster, or iconoclastic attack, or be used to track its condition through the stresses placed on the object by mass tourism. The “digital passport” provides objective evidence in the case of provenance and ownership disputes, insurance claims, and academic discussions.

Methodology of computer-assisted restoration

The methodology behind digital restoration is unique to the specific requirements of each project, although it is possible to loosely define a number of phases. Two case studies from the work of the Factum Foundation for Digital Technology in Conservation are used to illustrate the methodology of computer-assisted restoration.

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It is first necessary to define the parameters and scope of the digital restoration: What are the objectives? Is the final result virtual or physical? Is it for exhibition display or for the management of vulnerable or remote sites? Is it to reveal the changes an object had undergone? Is it to provide access to the object and reveal its importance? Is it for condition monitoring and to inform restoration decisions? The available materials will in part determine the course of action.

The initial steps involve obtaining color images and a geometrically accurate 3D model, which if possible also captures the subtle surface characteristics that condition our response to a work of art. It is important that the initial color recording is carried out at the highest possible resolution using composite photographic techniques such as panoramic photography, because the work to prepare and merge the image files—elimination of geometric/perspectival distortions and color management operations—reduces the resolution. The result of this step should be an image file that can be significantly enlarged with no loss of quality. All forms of mediation and transformation of the data result in an irretrievable loss and abstraction of information. It is therefore essential to retain both raw and processed files along with a complete history of the actions applied to the digital archive. The “transparency” of the image file will determine the value of a digital restoration, but also enhance the impact it can have as it informs diverse professional decisions.

The recording of 3D information is a relatively new and rapidly developing science. There currently exist a great variety of 3D scanners, each used to document a different aspect of an object or site. Light detection and ranging (LiDAR) scanners can be used to capture geometry quickly and accurately from distances of 1–300 m; white-light scanning technologies record both shape and surface texture from a range of between 0.5 and 1.5 m; and close-range laser scanning technologies can accurately record the surface of objects to submillimeter resolutions. Close- and long-range photogrammetry, a photographic technique to capture color and 3D information simultaneously, is relatively cheap to implement and rapidly replacing more traditional systems in heritage recording. It is currently the case that

the resolution of photogrammetric data cannot match other close-range scanning technologies in either 3D or color resolution. However, recent developments in software and capture methods are enabling conservators and digital restorers to start using photogrammetry as a way to capture surface relief, allowing significantly reduced recording times.

Once data have been recorded and processed, they can be made available to a wide range of specialists in easily accessible forms that are independent of expensive specialist software. These data will inform physical restorations and facilitate research into previous states of conservation by comparing these data with conservation reports, historical images, or accounts of the work of art. Other useful supporting materials may include preliminary sketches, prints, and contemporary copies. If the work is fragmented, damaged, or missing parts, the work of digital restoration will also necessitate academic research. This research will involve the identification of different elements of the same object, obtaining recording permissions, and capturing all fragments at high resolution to ultimately create a virtual or physical archive that reintegrates these elements.

The practice of “digital restoration” can work on many levels. Cracks on the surface of a painting can be analyzed, studied, and removed. Such processes can sometimes be automated using algorithms provided by the software or specially written to reveal the specific physical characteristics that are being studied. Areas of information loss can often be refilled either by cloning surrounding data (when the loss is very small) or by relying on secondary sources when the loss is significant. It is possible to use complex computational, and mathematical methods in the reconstruction of 3D objects, for example, to locate the position of broken fragments. Digital restoration can be performed as an end in itself, a way to better understand the object, or it could inform the physical restoration of a fragmented object.

In all cases, the goal is objective clarity and any changes to the original surface or color need to be “marked” in one way or another. This can be by clearly defining layers within an image file or by using different chromatic codes, to signify

that they are not simply restorations of existing information. Most restoration techniques have an equivalent in the digital domain.

Case 1: The Polittico Griffoni: reuniting and studying a fragmented altarpiece

The *Polittico Griffoni* is an important altarpiece of the Bolognese renaissance painted between 1471 and 1472 by Francesco del Cossa and Ercole de' Roberti for the chapel of San Vincenzo Ferrer in the Basilica of San Petronio, Bologna (Polittico Griffoni). Commissioned by the Griffoni family, the altarpiece remained in San Petronio until the early eighteenth century when the chapel came into the possession of the Aldrovardi family. The *Polittico* was then dismembered and the individual paintings sold. The sixteen surviving panels can be found in nine different museums around the world, including the National Gallery (London), the Louvre (Paris), the National Gallery (Washington), and the Pinacoteca Vaticana (Rome).

The project to reunify the panels of the *Polittico* and restore a facsimile to the chapel of San Vincenzo in the Basilica of San Petronio is a digital restoration aimed at nurturing a deeper understanding of the altarpiece and the artists who painted the panels (Factum Foundation 2018a). The first phase of the work involved composite photography to capture color and a high-resolution 3D laser scanner to record the complex surface of each panel. The recording was carried out over a period of three years in seven different countries. In one case, the data were used to assist restorers during physical restoration—where two panels were recorded before and after the intervention to monitor and document the process. In each case, the custodian will own the data for all current and future commercial applications. In return for this clear statement of ownership, each custodian has agreed to share the data for conservation and study with the other institutions which own parts of the whole ensemble. A digital version of all the paintings recorded will be supplied to each museum (or collection).

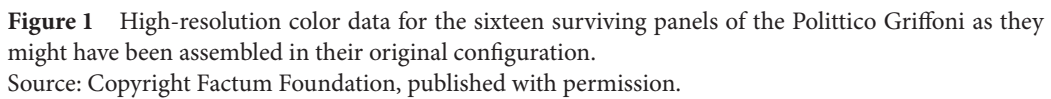
For each panel, it is now possible to view color and 3D information together or separately,

revealing things that cannot easily be identified with the naked eye. While this is leading to a clearer understanding of the reasons behind why each panel looks as it does, the most spectacular part of this “digital” restoration has been the production of a physical facsimile of each painting in its current condition. The individual paintings have been assembled based on new research into how the altarpiece looked when it was first installed in the Griffoni Chapel (Figure 1). The facsimile was installed in the Basilica, thus providing a new context for both the individual panels and the recently restored Griffoni Chapel, itself a historical reinterpretation by Bologna's controversial arts and crafts restorer Alfonso Rubbiani (1848–1913). “On-screen” visualizations may be presented in museums alongside the individual panels, informing discussion about the original design and context of the altarpiece.

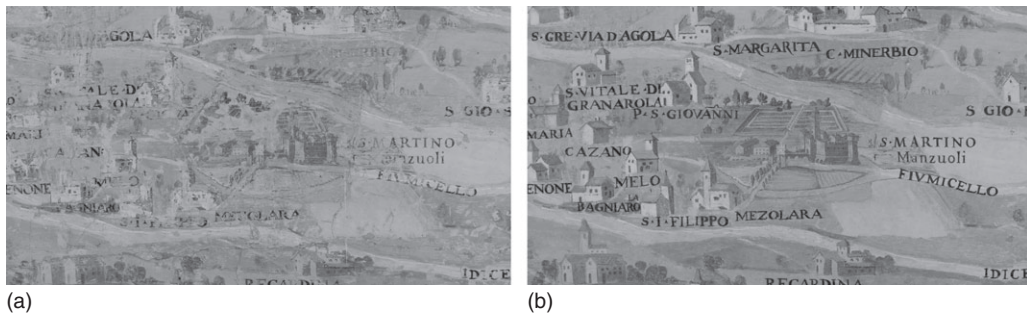
Case 2: Wall paintings of the Sala Bologna: digital restoration of lacunae and damaged toponyms

The wall paintings of the Sala Bologna in the Vatican were commissioned by Pope Gregory XIII in 1575 and executed under the supervision of Lorenzo Sabatini. The western wall of the room is almost entirely occupied by a bird's-eye-view map of the province of Bologna. The initial aim of this project was to make a facsimile of this map for the Museo della Citta. However, the facsimile generated interest from the University of Bologna for a virtual reconstruction of the *Map of the province of Bologna*, which would interpret and reintegrate missing areas based on maps and drawings that were discovered in Bologna at the time and other historical research. The digitally restored map gives the viewer a clear and vivid idea of the original appearance of the wall painting. The work was a collaboration between the Factum Foundation and the Alma Mater Studiorum at the University of Bologna, which carried out much of the toponymical research required to “fill in” the missing areas (Factum Foundation 2018b).

The frescoes were initially photographed using a panoramic recording system. This provided the high-resolution color information required



of crack and its location. This was followed by the reintegration of small losses in the landscape. Areas of the *Map* that retained abrasions and rubbings resulting in loss of information were digitally restored by employing both old and new



maps to define the locations of buildings and different features within the various townscapes. It was possible to reconstruct a number of larger lacunae (up to 0.5 m²) thanks to the existence of preliminary painted sketches. The castle of San Martino Manzuoli in Soverzano was reconstructed based on a drawing by Egnazio Danti, which contained sufficient detail to produce an accurate rendition of the missing section of fresco (Figure 2). The drawing was also used to recreate the castle grounds, although specific features were added based on written descriptions of gardens of the period. An interesting reintegration was carried out for a lacuna in the city of Bologna itself: By superimposing a contemporary map of the city over the image of the fresco, it was found that the missing area exactly corresponded with the Basilica di San Petronio. Adapting the design of the Basilica to the style of the map, the building was reconstructed and reintegrated into the representation of Bologna. Several areas that were found to have undergone previous physical restoration were digitally enhanced to “bring back” the appearance of the original. In the end, two versions of the *Map* were produced: one retaining the appearance of the restored areas, the other showing the *Map of Bologna* as it may have looked without historical restorations.

This project is an excellent example of the virtual integration of a number of different historical materials to produce a plausible non-contact reconstruction of the original appearance of a work of art. In the process of the virtual restoration, original research was carried out,

leading to a deeper understanding of the *Map of Bologna* and the biography of its creation.

Conclusion

A new key concept in the digital age is “non-contact,” and although the mantra of the conservation community used to be reversibility, this has recently come under pressure as both practitioners and the general public realize that it can be a relative concept at best and misleading at worst. Digital restoration can ensure that subjective and temporally located decisions are not imposed on original works of art. Moreover, it creates the space for detailed study to be carried out in tandem with restoration and conservation initiatives. Increasingly, digital recording technologies are also facilitating objective records that can be used to monitor change and ensure preservation is both collectively agreed and forensically sound. As exemplified by the case studies discussed above, digital restoration is emerging as a field that can lead to a deeper understanding of heritage and to the objective monitoring of physical interventions. It separates the necessity for subjective projections onto the original object from the desire to understand the original object more deeply. The relationships between originality and authenticity, facsimile, and the need to preserve works of art for future generations are very relevant topics in heritage management, particularly as the world’s population rises above seven billion and more and more people have the means and desire to travel. Pressure is mounting

on heritage sites for a variety of reasons and visitors will need to understand that there is a delicate contract between providing access and the destruction of the articulate evidence of the past.

SEE ALSO: Adobe; Computer Applications in Archaeology; Digital Heritage; Digital Photogrammetry; Laser Scanning

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FURTHER READINGS

Digital Cartography

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Space is fundamentally important to archaeology. From accessing archive information through to recording excavations, there is a heavy reliance on mapping. Over recent decades, there have been a number of parallel developments which have significantly enhanced the ability and rapidity of digital cartography, owing to the development of equipment for capturing data, the increased accessibility to existing digital data including archaeological records and mapping, and the software to process, integrate, represent, and analyze outputs.

While conventions exist regarding the representation of spatial data, the abstraction of space into any cartographic output relies on a number of fundamental considerations, including the spatial scale of the map, its orientation, and its position relative to known features such as roads or buildings. Surveying for the creation of maps can be either achieved in relation to established national, regional, or global coordinate systems which intrinsically reference scale and orientation, or undertaken locally within a “divorced” framework. Increased access to digital mapping resources and the increased sophistication of surveying equipment and data recording have disrupted such divisions. While traditional surveys were always undertaken in relation to the scale at which the mapping would be reproduced, the ability to rapidly collect highly accurate and detailed survey data and the use of digital cartographic techniques such as computer-aided design (CAD) and geographic information systems (GIS) (see Chapman 2006; Wheatley and Gillings 2002) have led to a blurring of issues of scale where survey data can be represented and investigated at varying resolutions. This, coupled with the ability to reproduce and re-task digital data for purposes different to those originally intended, highlights some of the

potential challenges to archaeologists generating digital maps.

Traditional cartographic approaches in archaeology, as elsewhere, relied principally on the measurement of angles and distances. Using equipment such as tapes and chains, coupled with prismatic compasses, optical squares, plane-tables, and theodolites, surveys were commonly undertaken as localized, divorced measurements that could later be manually integrated with existing mapping. These techniques required varying levels of mathematical skill, as reflected, for example, in the origins of the Royal Commission on the Historical Monuments of England within a division of the Ordnance Survey (see Bowden 1999). Typically, survey consisted of two elements: the generation of survey control which provided a network of known positions; and detail survey, using the established control points to pick up details for mapping, such as trench positions or find locations.

The development of digital cartography in archaeology was possible through technical advances in surveying equipment and computer hardware and software. The integration of automatic distance measuring within theodolites led to the creation of total stations (see TOTAL STATION) in the early 1970s which were able to measure angles and distances together through the integration of an electronic distance meter (EDM). This was further enhanced by the development of data-logging equipment that enabled survey positions to be collected automatically, and the increased ability of survey equipment to automatically calculate coordinate positions from angle and distance measurements. The subsequent development of robotic total stations has meant that survey data can be collected by remote control by a single surveyor, and integration with other types of surveying equipment has provided an increased level of freedom in addition to enhanced speed of data collection. Equally, the ability to collect data without the need for a prism has meant that the survey of inaccessible points has become possible.

Perhaps the single biggest impact on digital cartography in recent decades has been the

development of satellite navigation systems (see GPS (GLOBAL POSITIONING SYSTEM)). While commonly referred to as global positioning systems (GPS), there are two principal global constellations of satellites that are used for surveying: the US system called GPS and the Russian Federation system called GLONASS. Other systems in development that currently provide only regional coverage include the Chinese BeiDou system, the European Union's Galileo network, and India's NAVIC system. Collectively, such systems are known as global navigation satellite systems (GNSS) and can be used to establish positions using trilateration of distances from individual satellites calculated using radio transmissions.

In the early years of GNSS surveying there were issues over accuracy, such as the "selective availability" applied to GPS. However, satellite navigation is now providing high levels of accuracy, with the greatest use within archaeology being with survey grade accuracy (typically within approximately 2 cm three-dimensionally). Such accuracy can be achieved either by using two satellite receivers (one static and one recording detail) to correct positions, or through access to regional and national networks of GNSS receivers which can provide equivalent corrections via mobile networks (see Historic England 2015).

The impact of satellite surveying systems on archaeology has been considerable. The ability to directly generate accurate three-dimensional (3D) positions relative to national, regional, or global coordinate systems has significantly increased the ability to undertake control survey (for use by other surveying equipment) and for detail survey. Since GNSS primarily records data in relation to global coordinate systems, larger areas can be surveyed without the problem of elevation accuracy reduction due to Earth curvature. Consistent accuracy means that survey errors are not compounded, which is a hazard with optical methods of survey, and it has become possible to mount satellite surveying equipment on motorized vehicles for the rapid collection of positional information relating to extensive geophysical survey.

The increased rapidity of data collection facilitated by the development of surveying equipment,

in relation to both satellite-based and optical systems, has also increased the ways in which survey data can be used for cartography. In addition to the ability to generate digital mapping rapidly, the ability to collect large volumes of 3D position data has increased the ease by which representations of land surfaces can be interpolated within software packages such as GIS to create 3D representations (or, more strictly, 2.5D), including both general topography and earthworks (e.g., Chapman and Van de Noort 2001). In turn, this has led to the capability to perform spatial analyses of these elevation models to create more abstract representations of space such as of slope, aspect, or even visual relationships.

A fundamental shift in digital cartography has been the development of equipment, software, and approaches for collecting surface data, using techniques such as laser scanning (see LASER SCANNING) and photogrammetry (see DIGITAL PHOTOGRAMMETRY). Whereas other data collection methods normally focus on the subjective collection of specific positions from which digital maps can be created, these methods rely on total capture of data from a prescribed area. The advent of terrestrial laser scanning (see English Heritage 2011), for example, has altered the ways in which digital maps can be created in two principal ways. First, data are collected on the basis of point density rather than specific 3D points chosen by the surveyor. Second, and building from developments with other optical systems, laser scanning can generate 3D data which can represent 3D spaces.

While photogrammetric techniques have been used within archaeology for over a century, digital technology has made multi-image photogrammetry much more accessible and rapid, in addition to providing new tools for representing and analyzing the results. The proliferation of software packages, online tools, and mobile apps means that multiple photographs can be used to generate 3D models of an object or area (e.g., structure from motion (see STRUCTURE FROM MOTION)). This has given rise to the possibility of data-mining photographs of specific sites to generate 3D digital models, as is currently being used in areas of conflict where threats to heritage sites are significant. The current growth in the use of photogrammetry and its ability to be accessible through numerous, less specialist, and

sometimes freely available software is leading to a growth in this area. As with laser scan data, digital photogrammetry generates 3D data from which 2D plans and 3D models can be generated, albeit only after they have been tied into reference information regarding scale, position, and orientation.

The increased ability to generate 3D survey data, particularly from laser scanning and photogrammetry, has been mirrored by developments in software able to deal with the cartographic challenges that such approaches bring. The development of 3D spatial databases such as buildings management systems (BIMs) and other 3D software packages has realized the potential for generating 3D cartographic representations based on survey data. With the increase in the different software packages within which maps can be generated, each with varying levels of interactive capability, there has been some blurring of the boundaries regarding best practice, with the potential for re-tasking data for use in different software packages, including game engines.

Digital cartography is not only dependent on terrestrial survey. The uses of aerial photography (see AERIAL PHOTOGRAPHY), satellite imagery (see SATELLITE HYPERSPECTRAL AND MULTISPECTRAL IMAGING), airborne laser scanning (light detection and ranging (LiDAR); see Crutchley 2010 (see AIRBORNE LASER SCANNING AND LIDAR)), and, increasingly, drones (see DRONES) have provided an ever-growing suite of datasets for generating digital maps and layers of information to add to existing geographical databases. With varying levels of spatial integrity, these methods are generating new ways of capturing spatial data which can be used within cartographic software packages. With multispectral imaging and the ability to capture 3D data from airborne sensors, additional layers of archaeological information can be mapped which might not be visible on the ground or to the naked eye.

The continual development of hardware, software, and applications has meant that digital cartography is set to continue changing. However, despite the increased accessibility to these techniques at relatively low cost, there remain challenges. While survey data will normally be collected for a specific purpose, its “born-digital”

nature coupled with the potential to infinitely reproduce and re-use these data for other purposes raises challenges regarding its suitability, highlighting the importance of maintaining good metadata. This challenge is also seen in the digitization and re-use of data from paper archives where the derived digital version might be represented at scales and resolutions far different to those originally envisaged. A second challenge lies in the archiving of the raw and processed data stemming from digital cartography. The large volumes of data and numerous iterations, matched by the common need for specialist software to process it, mean that sometimes only the derivatives can be easily archived. A third challenge lies in the objectivity of the data themselves. The fundamental difference between surface data collection (e.g., through laser scanning or photogrammetry) and detail survey of 3D positions is that, while the former is effectively an objective record of what the equipment is able to record, the latter relies on specialist interpretation of the most appropriate locations to survey. Aside from the contrasting requirements in terms of expertise, a concern is that insufficient interpretation might be made in the field when collecting surface data, becoming increasingly reliant on what might be interpreted on a computer screen.

Digital technologies continue to make a fundamental impact on the capture and representation of space, through new tools for collecting data and new methods of representing and analyzing the results. While these tools have enabled archaeologists to achieve higher levels of accuracy and consistency, in addition to enabling new and exciting outputs, the shifts that this new technology has brought are also challenging the nature of archaeological survey, mapping, and archiving.

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Digital Models of the Land Surface (Digital Elevation and Terrain Models)

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It has long been recognized that topography and geomorphology are key elements in structuring the physical environment (see ENVIRONMENT AND LANDSCAPE) in which human activities take place and to which they relate. These elements include, among other things, settlement, land-use, resource exploitation, and movement. Direct relationships between topography and human activities include, for example, the presence or absence of obstacles to vision or movement, including sea-level change (see SEA-LEVEL CHANGE). Direct relationships can be distinguished from indirect relationships which encompass the topographically influenced presence or accessibility of resources, protection from natural or human threats, and cultural preferences. Examples of indirect relationships are soil differences between upper and lower slopes, exposure of mineral resources, presence of water, exposure to sunlight and precipitation, and presence of particular types of vegetation or fauna. Topography does not, however, determine human behavior. Rather, human response and adaptation to and utilization of particular environments are always subject to technology and culture.

Given the importance of topography and geomorphology as key environmental factors, digital models of the land surface are valuable datasets that can enable and enhance the understanding of past human–environment interactions. Hypotheses relating topographic variables to human activities are developed and tested and can, for example, be applied to “predict” the location of previously unknown archaeological sites (predictive modeling (see PREDICTIVE MODELING)). Furthermore, human activities

leave topographic traces by the intentional or unintentional removal, movement, or deposition of material. Such traces can be detected in high-resolution digital terrain models (DTM) and are frequently used in archaeological prospection.

Digital models of the land surface can broadly be divided into models of the actual ground surface excluding vegetation, buildings, and so on (DTM) and models including vegetation, buildings, and so on (digital surface models (DSM)). While some inconsistencies in the use of these terms prevail, the term digital elevation model (DEM) is often used either as an overarching term for both DTM and DSM or synonymously with DTM. These digital models are used in a variety of different data structures and file formats. The most common data structures are point clouds, triangulated irregular networks (TIN), and rasterized elevation maps. A point cloud contains X, Y, and Z coordinates of a large number of individual, usually irregularly spaced, points. A TIN contains X, Y, and Z coordinates of a large number of individual, usually irregularly spaced, points which are linked in a network of nonoverlapping triangles. A TIN is, after optional selective thinning, created from a point cloud by Delaunay triangulation that connects all points into triangles and ensures that none of the points is inside the circumcircle of any of these triangles. A rasterized elevation map contains a regular grid of elevation values. A rasterized elevation map can be created directly from a point cloud using binning and interpolation or from a TIN created as an intermediate product. The terms DEM, DSM, and DTM commonly refer to a rasterized elevation map but can also refer to a TIN.

Most analytical and visualization applications require continuous surfaces rather than individual points. While the nodes in a TIN commonly represent actual point measurements, the elevations in areas where no measurements exist are derived by interpolation based on neighboring points. In a TIN derived from digitized contour lines or from a gridded elevation map, all values are usually derived by interpolation. Different interpolation algorithms

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(e.g., bilinear interpolation, inverse distance weighting, kriging) exist and will produce different results. Results may differ by algorithm type and some may represent the true surface better than others or may be visually more pleasing (Mitas and Mitasova 1999). However, as interpolation does not add information, neither a TIN nor a rasterized elevation map can resolve detail smaller than the distances between actual point measurements. The application of digital elevation data at resolutions higher than that of the underlying elevation measurements is therefore problematic. The advantage of a TIN derived from actual point measurements over a rasterized elevation map is that the former preserves the measured elevation data and that it allows spatially variable point densities which can improve the representation of break lines. A rasterized elevation map has the advantage of smaller file size. This is because only elevation values have to be stored in a rasterized elevation map rather than X, Y, and Z coordinates plus edges in a TIN. A rasterized elevation map also allows the easier computation of parameters such as slope, aspect, and convexity or relief visualization.

There are various methods for the acquisition of digital elevation data. Traditionally, DTMs have been created from digitized map contours. Today, this technique is mainly used for the reconstruction of historical topography. Because ground-based topographic survey using the global positioning system (GPS) (see GPS (GLOBAL POSITIONING SYSTEM)), DGPS, or Total Station (see TOTAL STATION) is slow, most methods now rely on remote sensing (see AIRBORNE REMOTE SENSING) approaches such as airborne LiDAR, terrestrial LiDAR (see TERRESTRIAL LIDAR), synthetic aperture radar (see SYNTHETIC APERTURE RADAR) (SAR), or digital photogrammetry (see DIGITAL PHOTOGRAMMETRY). Digital photogrammetry uses image-based 3D modeling (see IMAGE-BASED 3D MODELING), multi-view stereo (see MULTI-VIEW STEREO), or structure from motion (see STRUCTURE FROM MOTION) with aerial photography (see AERIAL PHOTOGRAPHY) from various platforms including drones (see DRONES). Achievable spatial coverage and resolution, as well as penetration of vegetation, depend largely on the method of acquisition. For most applications in archaeology, airborne LiDAR has become the method of

choice due to its unmatched ability to penetrate forest canopy, its high spatial resolution, and potentially very large area coverage (Doneus and Briese 2011). Irrespective of the method of 3D point data acquisition, the raw point cloud usually contains a considerable quantity of non-ground points (commonly vegetation and/or buildings). Creating a digital model of the actual ground surface (a DTM) requires the removal of any such points. Technological progress in recent years encompasses increasing spatial resolution, improvements in vegetation filtering due to the application of advanced filter algorithms and full waveform scanners, and the possibility to penetrate shallow water with bathymetric LiDAR (Doneus et al. 2013). SAR, specifically the near-global shuttle radar topography mission (SRTM) DSM, is frequently used when the topography of very large areas is analyzed. Image-based 3D modeling is used in particular for the generation of local DSMs (and DTMs in nonvegetated areas) and is praised as a rapid and low-cost approach.

A major motivation for using digital models of the land surface in archaeology is the enormous analytical and modeling potential of such data (Opitz and Cowley 2013), in addition to the often compelling visual impression and the landscape-scale presentation of archaeological sites and their environments. Computations of slope, aspect, relief curvature, automated landform classification, and the modeling of environmental parameters with the aid of topographical data (such as wetness indices, runoff and erosion potential, and soil properties) provide baseline data for assessing archaeological sites and their environments. (Inter)visibility modeling (see VISIBILITY MODELING)/isovist analysis (see ISOVIST ANALYSIS) can be performed for different scenarios using a DTM, actual DSM, or modeled DSM with known or hypothetical past vegetation cover (Wheatley and Gillings 2000). Modeling of solar illumination and derived parameters under such scenarios can provide insights into microclimatic conditions at site and landscape scale and can in turn be used in vegetation modeling. Computations of topographical prominence can be based on known or hypothetical perceptions and functions of landscape elements and can be used to assess hypotheses regarding site placement and

function. Cost-surface analysis and least-cost paths (White and Surface-Evans 2012) provide tools for testing hypotheses about known routes, as well as for finding unknown or likely routes. For modeling results to be relevant to the archaeological questions posed, all relevant assumptions must be stated clearly and, if possible, be justified by evidence. Finally, digital models of the land surface are key elements in virtual reality modeling (see VIRTUAL REALITY MODELING) applications at landscape scales.

Perhaps the most common current application of high-resolution digital terrain models is archaeological prospection. This has rapidly gained importance with the increasing availability of high-resolution DTMs derived from airborne LiDAR (Doneus and Briese 2011). As many human activities such as agriculture, mining, movement/transport, settlement, and ritual have left traces in the topography, these traces can be used to detect and map archaeological features and sites. Such mapping efforts have contributed to the recognition of archaeological landscapes and the trend of considering archaeological evidence and interpretation at a landscape scale. Because many traces of past activities are relatively minute in comparison with the landscape forms on which they are superimposed, advanced LiDAR data visualization and processing techniques (e.g., Štular et al. 2012; Kokalj and Hesse 2017) are increasingly used to generate data products that facilitate archaeological interpretation (see LIDAR DATA VISUALIZATION AND PROCESSING). Together with the penetration of forest canopy and the availability of LiDAR data for very large areas, the resulting ease of desk-based mapping and prospection has led to a revolution in how landscapes are treated in archaeological research (Chase et al. 2012).

With increasing spatial coverage, availability, and resolution of DEM and the ongoing development of analytical tools, including geographic information system (GIS) and relief visualization techniques, an increasingly widespread use of such data can be observed. Visual presentation and spatial analysis of archaeological sites and landscapes, as well as large-area archaeological prospection in forested areas, now commonly rely heavily on the application of digital models of the land surface. While the technological advances and the increasing focus on quantitative

approaches have indeed been revolutionizing archaeological practice, their implications for archaeological theory may require more attention (cf. Verhagen 2012).

SEE ALSO: Airborne Laser Scanning and Lidar; Digital Cartography; Laser Scanning; Spatial Analysis

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Digital Photogrammetry

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Digital photogrammetry is an image-based, three-dimensional (3D) measuring technique that typically involves a series of digital images where subsequent camera locations and orientations produce overlapping views of an object (e.g., a ceramic pot or stone structure) or a surface (e.g., a landscape from an aerial perspective). The overlapping portions of each image pair (known as a stereopair) provide the stereoscopic parallax required for most photogrammetric processes, including the measurement of discernable points in 3D space. To be precise, digital photogrammetry includes measurement techniques involving a single image, but the term is predominantly used to refer to stereophotogrammetric methods, which will be the primary topic of this definition.

Digital photogrammetry is a flexible and relatively straightforward process, making it useful in a wide variety of scientific and commercial applications. These applications range in scale from astronomical (e.g., measuring the position of celestial objects) to near-global (e.g., using large collections of satellite images to model the Earth's surface) to microscopic (e.g., using photomicrography to measure small objects not visible to the naked eye). These applications can also range in monetary cost from extremely expensive to nearly free (assuming users already own a digital camera and computer).

Digital photogrammetry can potentially involve a number of different input data types, including images from both active (e.g., radar or sonar) and passive (e.g., photographic) sensors. The most common sources of imagery are sensors found on imaging satellites, aerial camera systems, digital single-lens reflex (DSLR) or other consumer-grade cameras, and digitized film-based photographs (e.g., scanned historic aerial photography). Image sets for a given project can be captured by a single device from multiple

locations, or by multiple devices stationed at various locations. If a single imaging device is used, the subject and surrounding scene are typically static. When multiple, synchronized imaging devices are used, a single instance of a moving object or scene can be captured.

At the most basic level, photogrammetry is accomplished by calculating the 3D intersection of two or more vectors that are defined by the relationship of (1) a measured point on an image, (2) the location and orientation of the camera at the time of image capture, (3) the intrinsic properties of the camera and lens used to capture the image, and (4) the position in 3D space of the point measured on the image. This relationship is described by collinearity equations and, during the photogrammetric process, is iteratively refined by a process known as bundle adjustment (Brown 1976).

The two basic categories of photogrammetry are aerial photogrammetry and close-range photogrammetry (CRP). Industry and research applications of both aerial and CRP vary widely. From the doctor's office to the manufacturing floor, photogrammetry is used to quickly reconstruct accurate 3D models of real-world objects and to guide automated processes. These models and processes include a range of scenarios, such as mapping and survey, spatial analysis (see SPATIAL ANALYSIS), site/object documentation and dissemination, 3D feature extraction, rapid prototyping, tool/part inspection, deformation monitoring, clash detection, automated part assembly, motion tracking, robot navigation, and many others.

Aerial photogrammetry is defined by the use of digital images with an aerial perspective captured by a camera or other digital sensing device while mounted to an aerial vehicle or imaging satellite (see AERIAL PHOTOGRAPHY). These images are commonly used to create mapping products, such as digital surface models (e.g., a digital elevation model of the Earth's surface) and orthorectified images (geolocated, near distortion-free images with map-like properties). Traditionally, aerial photogrammetry involved

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carefully planned flights using aircraft rigged with specially designed and calibrated film-based metric cameras. Today, a wide variety of aerial- and orbital-based digital sensing devices exist. Global navigation satellite systems (GNSS) and modern photogrammetric software provide, in some cases, automated tools for calibration of geometric and radiometric sensor properties, and the output of map-ready digital files useful to a wide variety of users.

CRP involves images captured from some lesser distance than aerial photogrammetry, including images captured from low-altitude aerial (e.g., low-flying unmanned aircraft systems (UAS)) and/or terrestrial based platforms (e.g., a standard tripod). Image sets for CRP can be captured in a relatively short amount of time and do not require a professional-level DSLR. Regardless of what camera is used, the photographer will ideally have the skills necessary for taking sharp, well-exposed photographs that frame the object tightly, making efficient use of the available sensor area. Common uses for CRP include the 3D documentation of structures or objects, crime scene investigation, and metric analysis of complex objects or surfaces.

For any digital photogrammetric project, the potential density of measurements and precision with which any individual measurement can be made will, in part, be connected to (1) the distance from the camera to the object, (2) the sensor size/resolution of the camera, and (3) the focal length of the lens. Together, these three variables determine the size that any given pixel in an image occupies on the surface of the subject being imaged. This value, equal to the distance between the center of two adjacent pixels as measured on the subject's surface, is known as ground sample distance (GSD). Projects are commonly planned with GSD in mind, as it can be a limiting factor for the usefulness of certain project outputs.

Aerial and CRP projects involving a surface (e.g., a landscape or vertical wall-like surface) will typically result in one or more linear strips of parallel stereo images. In this case, the optical axis of each camera location is parallel to one another and do not intersect. To ensure complete coverage, camera locations are usually arranged in blocks where the viewable area of subsequent images within a single strip will contain 60–90 percent forward overlap, and subsequent strips

will contain 50–70 percent side overlap. Projects involving an object imaged from multiple angles will result in an image dataset of convergent stereo images, meaning the optical axes of subsequent camera locations will intersect at some point in space.

Inherently, the scale, position, and orientation of any photogrammetric model is arbitrary, although most software will initialize the coordinate system using the location and orientation of the first camera station. Therefore, projects requiring the photogrammetric model to be accurately scaled or situated within an existing reference frame will need to integrate sufficient reference points with known dimensions and/or coordinates. These reference points are commonly referred to as ground control points, or simply control points. As a minimum, reference information required for scaling a photogrammetric model would include a scale bar or other object of known length visible in two or more photographs, or two control points (also visible in two or more photographs) with known 3D coordinates. Beyond scaling, the orientation of a photogrammetric model requires, as a minimum, two control points with known 3D coordinates and one control point for which only one coordinate (x , y , or z) is known.

The accuracy of the reference information used to scale the photogrammetric model will determine the scale-accuracy of any data output. If the minimum control is provided for model orientation, then the accuracy of that reference information will only affect the position and orientation of the model within the reference frame, and will not contribute to the relative accuracy of the output model except for scale. If more than the minimum control is provided for model orientation (i.e., three or more control points with known 3D coordinates), it is important to understand that the accuracy of these control points can (depending on the settings within the photogrammetric software being used) influence all aspects of the photogrammetric solution (e.g., refinement of camera calibration, determination of image locations/orientations, and ultimately 3D model shape), in addition to the position and orientation of the model within the reference frame.

The history of photogrammetry is long. Well before digital photogrammetry (in fact, well before the invention of photography), scientists

were developing the mathematic principles required for such work. For example, publications on linear perspective in the early eighteenth century were proposing its usefulness in cartography. By the end of World War II, aerial photogrammetry was widely used for the production of topographic maps, one of the earliest and most dominant applications of photogrammetry (Wolf and Dewitt 2000). Around this time photogrammetry was done in an analog fashion with mechanical instruments; hence this phase of photogrammetry is now referred to as analog photogrammetry. The next phase, starting in the late 1950s, introduced computers to the photogrammetric process, which provided the computational power necessary for applying previously known mathematical principles. This phase is now referred to as analytical photogrammetry.

The beginnings of digital photogrammetry (circa 1990s) involved a move to fully digital setups, including computer-based photogrammetric software and digital images. This removed some of the complicated steps involved with earlier phases, but still included rigid conditions for camera calibration, image capture (camera settings and location selection), and overall processing, which remained a tedious and primarily manual operation. While this may still be true for projects requiring the highest degree of accuracy, digital photogrammetry today can be used to produce high-quality 2D mapping products and/or 3D models using inexpensive, off-the-shelf, nonmetric cameras and free, open-source computer software or web-based (cloud computing) services that are highly automated and easy to use.

Increases in computer processing speeds and memory over the past decades, along with advances made in computer vision research, have triggered an acceleration in the use of digital photogrammetry. Feature detection algorithms from the field of computer vision (namely SIFT, or scale-invariant feature transform, but also other similar object recognition methods) have led to the development of important image-based 3D reconstruction algorithms. The introduction of structure from motion (see *STRUCTURE FROM MOTION*) and multi-view stereo (see *MULTI-VIEW STEREO*) techniques to the photogrammetric process have essentially removed some of the

cumbersome requirements and time-consuming procedures associated with photogrammetric data capture and processing. Perhaps more importantly than making the photogrammetric process easier, these techniques have also increased the density of measurements that can be made with photogrammetry within a short period of time.

It is now possible to produce a single 3D measurement from nearly every pixel of every image within a photogrammetric project, easily obtaining millions or even billions of individual measurements. The product of this dense collection of measurements is commonly referred to as a 3D point cloud. Dense 3D point clouds can then be used to create a mesh of connected polygons, essentially defining the surface of the originally surveyed object. Current trends include the use of 3D polygonal mesh models in downstream software packages and digital environments such as computer-aided design, geographical information systems, 3D animation and gaming, augmented reality (see *AUGMENTED REALITY*), and others. These models can also be shared among researchers and/or the public for the purposes of research and education in the form of 3D printing (see *THREE-DIMENSIONAL (3D) PRINTING AND ADDITIVE MANUFACTURING*), interactive virtual worlds or games (see *VIRTUAL REALITY MODELING*), web-accessible virtual museums, and archival databases.

It is quickly becoming clear that the use of UAS will have a profound effect on a number of industries involving photography, videography, survey, search and rescue, and many others. This will likely lead to an increased awareness of the many uses for photogrammetry and other remote sensing technologies. CRP projects have always benefited from inclusion of images captured from an elevated perspective, and UAS clearly provide this at a lower cost than traditional aerial platforms. UAS can be piloted by a human operator or execute a predetermined flight path in a fully automated fashion, returning to some home base once the flight is complete. This technology, which can be used to provide repeatable high-resolution image datasets for photogrammetric processing, is already being used for a number of industries involving an often changing landscape, such as precision agriculture, and have

enormous potential for the monitoring of fragile and/or threatened archaeological landscapes.

SEE ALSO: Airborne Remote Sensing; Computational Photography; Computer Applications in Archaeology; Image-Based 3D Modeling; Photogrammetry and Stereophotogrammetry; Structured Light Scanning

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Geometric Matching

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Objects of interest in archaeology and many more domains are often characterized by geometric properties, which in turn may determine important aspects like shape and function. Geometric matching is the problem of finding correspondences between geometric representations, which in turn are obtained from appropriate notions of similarity of object geometry. Practically, object geometry is most often described in two-dimensional (2D) or three-dimensional (3D) Euclidean space. Computational methods for geometric matching provide a basis for many useful applications in archaeology (see *COMPUTER APPLICATIONS IN ARCHAEOLOGY*). For example, in virtual restoration (see *COMPUTER-ASSISTED RESTORATION*), the automatic reassembly of 3D models from digitized object fragments can be realized by searching for geometric matches between fracture surfaces. Also, object self-similarity can be computed by geometric matching, allowing researchers to paint-in missing parts of an incomplete object using input from the object itself. For 3D digitization, often many 3D views from a given object need to be merged, and matching of overlapping parts of these views can help to automatize this process. Also, matching can be applied to automatically identify correspondences between object parts (see *CORRESPONDENCE ANALYSIS*), supporting object analysis and interpretation. As a further example, geometric matching can be used to implement geometric search engines, allowing users to retrieve geometrically similar objects from object databases. While the focus of this survey is on methods for geometric matching in the 3D case, many methods can be adapted to also work for 2D situations.

Matching models

Geometric matching methods can be roughly divided into two general categories. Feature-less algorithms determine the matching between geometric surfaces by taking into account every point that belongs to these objects. In contrast, feature-based algorithms accelerate the matching procedure by first determining a set of salient feature points (or simply features) on the surfaces of interest and then trying to determine correspondences between these feature points. This way, the size of the problem is reduced and the computational efficiency is improved. However, determining reliable features can be very challenging when large amounts of noise exist in the input data, something that happens when scanning reflective objects using optical data acquisition methods or when using low-cost and low-precision 3D scanning devices. For these reasons, both feature-less and feature-based matching algorithms are used in practice, depending on the characteristics of each dataset.

Feature-less and feature-based geometric matching methods mostly take into account the geometry of the surface. However, their precision can be improved by using additional information when available, such as material or texture properties.

Feature-less matching

Finding the optimal geometric matching between multiple surfaces is a challenging optimization problem, where a search algorithm must search between many, if not all, possible solutions in order to find the optimal one. Local matching algorithms search around an initial starting solution for a locally optimal one, while global algorithms search, or stochastically sample, the entire space of possible solutions to find the globally optimal one. Global algorithms often trade matching accuracy for a more efficient inspection of the entire search space, but after they approach

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the optimal solution, they can be combined with a local algorithm for improved accuracy.

Local geometric matching is usually performed with the iterative closest point (ICP) algorithm, or one of its variants. This algorithm iteratively alternates between a correspondence determination step and a rigid-motion computation step. In the first step, closest-point correspondences are determined between the two shapes, where each point of the first shape is assumed to be corresponding to the closest point from the second one. Given these correspondences, the second step analytically computes the optimal rigid motion that aligns the shapes. After rigidly moving the shapes according to this computation, the same process is repeated iteratively. After a few iterations, the algorithm converges to a locally optimal solution that aligns the two shapes, a process that is also called registration. If a matching score is required, it can be computed by measuring the quality of the alignment (such as the average distance between the two surfaces). Many ICP variants improve the convergence speed and/or the robustness to noise and outliers.

As a local registration algorithm, ICP can determine the globally optimal alignment only if the initial pose of the shapes is close to the optimal one. When this is not the case, ICP should be combined with a global registration algorithm. Such algorithms are often based on well-known global search methods, such as simulated annealing, random sample consensus (RANSAC), or geometric hashing.

In simulated annealing, the matching problem is modeled as a function of six continuous variables: three for the position and three for the rotation. Given that these variables define a specific alignment, an objective function can evaluate the matching score as the distance between the two objects. The algorithm stochastically searches the entire space of possible solutions, starting from a (possibly random) initial position and jumping to neighboring solutions, by changing (or jittering) one or more variables. The direction and the length of the jumps depends on the values of the objective function at the current and previously visited points of the search space. Given enough iterations, the algorithm will approach the optimal solution, which can then be accurately determined with ICP.

Similar to simulated annealing, RANSAC is also a stochastic search algorithm, where the algorithm iteratively generates a random solution (hypothesis) to the problem and then tests it for correctness. The algorithm terminates when the probability of finding a better hypothesis is lower than a threshold. In geometric matching problems, the hypothesis can be generated by selecting a set of random points from the first surface, and then trying to determine an equally numbered set of corresponding congruent points in the second surface. The transform that aligns these two sets of points forms the hypothesis, which is then tested by measuring the geometric distance of the transformed surfaces.

Geometric hashing provides an alternative method to search the six-dimensional space of possible alignment transformations. First, the search space is quantized into nonoverlapping cells, and then for random pairs of congruent point-sets from the first and second shape, the transform that aligns these sets casts a vote to the corresponding cell. After taking multiple random pairs, a matching score can be determined by applying the transformation with the highest number of votes and counting the amount of overlap in the transformed shapes.

Geometric matching algorithms, such as *k*-sparse (Mavridis et al. 2015), can also be used to detect symmetries in an object, by registering an object with itself and enforcing partial-overlap or by reporting all possible solutions to the user.

Feature-based matching

In feature-based methods, the matching is based on certain shape features computed during a feature detection and description stage. Depending on the implementation, they can be computationally efficient as they may take into account a smaller amount of information as compared to all points of the input geometries. Also, depending on the feature definition, feature-based methods may implement shape abstractions, allowing them to match geometry under invariances (e.g., regarding noise, scale, level of detail, or nonrigid deformations).

One may distinguish global and local feature-based methods. Global features are computed

taking all input geometry into account. The main classes of global features proposed to date include view-based features (e.g., computed from renderings of the geometry), structural features (e.g., computed from line skeletons of the geometry like medial axis), surface features (e.g., computed from surface curvature), or volumetric features (e.g., volume histograms). Geometric features can be encoded in appropriate data structures including vectors, graphs, or histograms, yielding so-called geometric descriptors. The matching problem can then be solved by computing an appropriate distance function between pairs of geometry descriptors, and declaring a match based on thresholding the feature-based distance scores. Feature-based methods are often used in combination with statistical data analysis (e.g., for dimensionality reduction or feature selection to obtain compact descriptors); for comparative surveys of global geometry features see Tangelder and Velthkamp (2008) and Bustos et al. (2005). Recently, deep neural network technologies in combination with views of the considered geometry have shown to be effective for classification and feature extraction (Bai et al. 2016).

In contrast, local features are computed in particular regions of the geometry, with predominance of distinctive regions. Again, local features can be also encoded in vectors which can be subsequently analyzed using an appropriate distance. The local characterization of the geometry allows us to include robustness to transformations or missing geometry, which is a common problem in archaeology. For example, broken objects could be considered as partial shapes that can be reconstructed by using templates derived from similar models found in a shape repository (Savelonas, Pratikakis, and Sfikas 2014). Moreover, the study of local patterns in the heat distribution of surfaces has proven to be an effective way to find symmetrical structures in heritage objects (Sipiran, Gregor, and Schreck 2014). Symmetric correspondences can be found using a matching algorithm that counts validation votes based on geometric predicates. Subsequently, the symmetric correspondences with a high number of votes generate a symmetric transformation which, once applied to the original model, is able to generate missing portions of the object. This approach can be used to complete damaged archaeological objects.

Summary

Feature-less and feature-based methods allow us to implement geometric matching, which is needed in many applications dealing with 3D object data. The choice of method will typically depend on the practical requirements at hand, including the need for matching precision (possibly under invariance and robustness requirements), as well as computational efficiency. We note that feature-less and feature-based methods need not be used exclusively, but may be applied in combination. For example, efficient matching for large shape datasets can be implemented by first running a fast feature-based filtering stage, followed by a computationally more complex, but more accurate feature-less matching stage for refinement of the results.

SEE ALSO: Exploratory Data Analysis (EDA); Three-Dimensional (3D) Printing and Additive Manufacturing

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Geometric Modeling

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Archaeological research is largely based on the systematic excavation and analysis of material culture to interpret the three-dimensional (3D) world of past societies. Geometric modeling approaches may be applied to objects, features, and structures that were integral to the *milieu* of lifeways at the intersection of cultural and natural realms.

Overview

Geometric modeling, also known as computer-aided geometric design (CAGD), has become increasingly important to archaeological documentation, analysis, and interpretation. Geometric modeling is the study of computational and geometric aspects of curves, surfaces, and volumes. It is an inherently interdisciplinary area, drawing from a body of knowledge including mathematics, engineering, and computer science.

Traditional application areas included computer-aided design (CAD) systems used by engineers and designers, games and movies, scientific visualization, and medical image processing. With advances in data capture, increased computing speed, and less-expensive storage, more disciplines have access to 3D data and thus a desire to describe shapes and analyze these representations. Hence, geometric modeling has become an important tool for scientific domains such as archaeology. The geometric modeling toolkit can be separated into three phases: data capture, creation of geometric models, and geometric analysis.

Data capture

Data capture, also referred to as digitization or scanning, pertains to capturing inherent details of a physically existing form into a digital representation. Data capture can be regarded as a discipline in its own right (Farin, Hoschek, and Kim 2002) and various data capture methods are employed including photography, generating pixel data (see COMPUTATIONAL PHOTOGRAPHY); laser scanning, generating 3D point clouds (see LASER SCANNING); remote sensing (see AIRBORNE REMOTE SENSING) and computed tomography (CT) scans, generating volume data (see COMPUTED TOMOGRAPHY).

Geometric processing methods are essential to preparing data for representation and analysis. A triangulation must be computed for a 3D point cloud, imparting a topology to the data and also converting the point cloud to a surface representation. Geometric decimation methods and mesh optimization are essential for creating optimal-sized datasets, removing redundant data, or improving visualization. Detecting noise and removing it from the data is also important (Farin et al. 2002).

Features refer to attributes (shape, color, texture, functionality, etc.) that are important to the particular domain community. Segmentation is defined as breaking down an object into a set of simpler objects based on features. Segmentation can be hierarchical. For example, a vessel could be defined as a combination of base, body, neck, and spout. The body itself may comprise several functional elements. Feature identification and segmentation is important for making the data more manageable and improving the representation (Schurmans et al. 2001; Razdan et al. 2004).

Model creation

Representation of geometric surface models can be carried out with triangle meshes or as a set of explicit, implicit, or parametric equations (Farin et al. 2002). For continuous surface models, the latter is the favored method because of flexibility

in design and ease of analysis. The final representation may depend on many factors, such as storage space, precision and accuracy to recover original data, and ease of downstream data usage. Bézier and B-spline parametric curve and surface representations are the most prevalent because they offer geometrically intuitive control polygon-based design handles (Farin 2002). These surfaces are sometimes called free form surfaces or sculpted surfaces. They are made of polynomial functions in each coordinate. If an exact representation of conics (e.g., ellipses) or quadric surfaces (e.g., spheres) is to be modeled, then nonuniform rational B-splines (NURBS), which are based on rational polynomials, should be used (Farin 2002). A parametric curve or surface can be readily analyzed or put into a simulation model. Additionally, modification of a parametric curve or surface is far easier than editing a triangle mesh.

Geometric models may be constructed as the solution to a data-fitting problem or in a design scenario. Least-squares fitting of a B-spline surface is the most common method for finding an approximation to 3D point cloud data (Farin et al. 2002). Complex datasets necessitate segmentation of the data into similarly shaped, continuous regions; this can aid in determining necessary parameter values for each data point. Smoothing equations for improved shape, called fairing, are easily employed, but at the expense of quality of fit.

For some applications, a triangle mesh representation might be sufficient, particularly since laser scanners can produce very dense point clouds. Geometric analysis methods, many of which are based on ideas from continuous geometry, can be approximated on a triangle mesh. Somewhat related to triangle meshes are the methods of subdivision surfaces, which take a polygonal mesh as input, carry out refinement steps, and result in smooth-looking surface models. Model design time can be quite fast and these methods are popular in areas where visual appearance is important but tolerance and analysis are not.

A large part of geometric modeling is concerned with the construction of continuous geometric models. A wide range of construction techniques are available for surface models. For example, the Coons method is based on

building a surface between four given boundary curves (Farin 2002). For example, a region of a ceramic pot that was missing can subsequently be filled in. CAD systems offer a wide range of construction techniques geared toward particular design scenarios and nearly all CAD systems are based on rectangular patches built as B-spline or NURBS surfaces. Volume modeling methods deal with visualizing scalar, vectors, or tensors in 3D space. A popular surface extraction technique, called marching cubes, generates contour surfaces as triangular meshes (Farin and Hansford 2000).

Geometric analysis

Many curve and surface interrogation methods are available. Curvature plots and comb plots for curves and curves on surfaces are available in nearly every CAD system. For surfaces, Gaussian curvature is widely used to analyze local surface geometry by classifying surface shape as one of three fundamental surface types: elliptic, hyperbolic, or parabolic. Gaussian curvature may be color coded and texture mapped onto the pot. Other surface curvature measures include mean, absolute, and root-mean-squares curvature. These measures reveal shape characteristics and irregularities of the surface, including profile or planar section analysis. Curvature of a planar section is analyzed to check for symmetry of the object. Additional examples of surface interrogation techniques include contouring, reflection lines, and geodesics (Farin 2002).

Archaeological applications

As technological advances in data capture hardware and software have been realized, applications to archaeological research have expanded rapidly to include microscopic phenomena, objects and artifacts, structures and architecture, and settlement systems and natural landscapes.

Archaeological analyses of natural and cultural objects and artifacts utilize geometric modeling to visualize internal features (volume modeling) and external features (surface modeling) (Schurmans et al. 2001). Internal cellular structures are modeled as they form and change

over time and modeling of articular joint surfaces facilitates studies of biomechanics. Modeling conjoinable surfaces can assess lithic reduction sequences. Variation and symmetry in ceramic vessel morphology provides measures of standardization. In reductive and additive technologies, geometrically meaningful features are identified as geometric pattern primitives, and their segmentation refines evidence of technological traditions.

Subterranean 3D surveying, scanning, and geometric modeling are contributing to accurate georeferenced mapping of natural and cultural features in cave sites (González-Aguilera et al. 2009). Terrestrial laser scanning produces integrated multiscaled models of geological formation processes and Paleolithic art applied to dimensional surfaces. Time-of-flight pulse and triangulation scanners used with artificial targets register datasets to a common reference system. Digital photography provides detailed color and textural maps. Processing proceeds from point cloud, to 3D mesh, to feature extraction and matching, to co-registration and computational parameters. Geometric CAD models have been used to construct cave replicas (e.g., Altamira) that are open to visitors while reducing impacts on the delicate sites.

Architectural studies of domestic, public, and religious structures present unique construction materials and techniques, preservation, and internal and external configurations. Traditional plan and profile drawings and photography are 2D, but are limited in perspective, accuracy, and interpretation. Architectural knowledge is developed with interdisciplinary discussion and analysis of junctures between cultural and natural forms (Colonnese, Carpicci, and Inglese 2016). Architectural complexities are illustrated with georeferenced altitudinal topographic models that detail the relationships among structures, landforms, and connecting passageways. Geometric models provide accurate 3D relational contexts to examine hypotheses regarding access, construction, and cultural relationships.

Geometric modeling and analyses are also applied to irregular earthen and shell mounds (Magnani and Schroder 2015). Model building from stereo photogrammetry (see DIGITAL PHOTOGRAMMETRY) generates mound size and

volume, details erosional processes and modifications, and provides 3D templates for restoration efforts. Techniques including structure from motion (see STRUCTURE FROM MOTION) (SFM) can provide accurate yet efficient methods of architectural documentation and guides for restorations.

Exploration of settlement patterns and landscape use in tropical settings has been thwarted by inaccessibility and vegetation overgrowth of architectural ruins and agricultural modifications. Recent advances in aerial light detection and ranging (LiDAR), where point cloud data have been filtered to remove noise from vegetation, have produced accurate and detailed modeling of ancient Mesoamerican structures, settlements, and agricultural terracing (Carter et al. 2012). International terrestrial reference frames with X, Y, and Z and global positioning system (GPS) coordinates also produce accurate geometric model maps of feature dimensions and elevations.

Future directions

Geometric modeling has opened a new era of exploration that benefits archaeology, geomorphology, and geology. We have outlined a pipeline of geometric modeling tools and given examples of their use in archaeological research. Advances in these tools can be made with more collaborative, interdisciplinary projects between domain scientists and the geometric modeling community, building custom tools for specific applications. These collaborations are most successful when the domain scientists become familiar with the vocabulary of geometric modeling. Additionally, an understanding of what underlies software applications for geometric modeling and visualization can help avoid producing erroneous results. The references provided are good starting points to explore key concepts and additional resources.

Future collaborations can contribute to building better geometric models more efficiently. Also, more advanced analytical capabilities to work with geometric models would provide researchers with better tools to extract measurements and define quantifications and dimensional

aspects of interest for comparative research. In turn, these capabilities will improve indexing and querying multiple models in large-capacity databases. Advancing geometric documentation and knowledge of heritage materials will support preservation efforts in recording sites, features, and artifacts for posterity, especially with continuing risks of damage or destruction through acts of conflict, vandalism, and natural disasters.

SEE ALSO: Airborne Laser Scanning and Lidar; Geometric Matching; Image-Based 3D Modeling; Lidar Data Visualization and Processing

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Human–Computer Interaction Research

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The study of the connections and interdependencies between humans and machines has been a constant focus of interest for research communities since historical times. Historical processes such as industrialization, arms development during World War II (e.g., the foundation of the Ergonomics Research Society in 1949 (Dix et al. 2003)), and the emergence of personal computers and personal applications (such as text editors and spreadsheets, or personal consoles for videogames) resulted in the formation of a new research area by the late 1970s. This new research area specialized in studying the relations between computer technology and human users. In particular, the rise of personal computing has been considered to be the main factor in the expansion of interest in human–computer interaction (HCI), bringing to this new area professionals from different disciplines and research backgrounds, and integrating and conciliating their different approaches. There have been significant changes with regard to the practice of activities related to information systems, due to the emergence of internet, mobile, and ubiquitous technologies, which have placed HCI research at the forefront of interdisciplinary research in the subdisciplines of computer science.

Even though this multidisciplinary presence enriches HCI research contributions, this diversity means that there is no general consensus about the set of the activities that are part of it (Ferre, Juristo, and Moreno 2003). On the one hand, there are approaches that study how computer technology influences all facets of human beings from a humanistic point of view. Considered part of the subfield called media studies, these approaches have become an autonomous research field separate from HCI research itself,

presenting research mainly in anthropology, ethnography, and journalism-based studies, but also incorporating in some cases archaeological professionals and visions.

On the other hand, there are new areas of knowledge that study the adaptation of computer technology solutions to the intrinsic characteristics of the human being from an engineering perspective, both physically (in areas such as ergonomics, etc.) and cognitively (adapting machine processes to the senses, emotions, and aspects studied in human cognition). This approach is considered today the main focus of HCI research, involving a multitude of studies that have something to contribute to the design, implementation, and evaluation of interactive systems in the context of tasks and works performed by one or multiple users (Dix et al. 2003) and the impact that computer technology solutions have on the users themselves. This is highlighted in a number of distinct research areas:

- The study of human cognition, how humans provide inputs to computers, and how they understand and process the outputs. These studies include user studies and user models, mental and memory models, information processing capacities, reasoning and knowledge formalization, and visual, hearing, or other sense-related studies that can be used as input/output channels for interacting with the computer.
- The study of the interaction channels of the computer (or any technological device with processing capabilities), mainly focused on the interfaces and the different interaction paradigms that can be offered in interaction (graphical, based on natural language, and ubiquitous, based on collaborative interaction, among others). Currently, some relevant research lines are:
 - The development of new techniques and methods for immersive environments, which allow wholly different interactions between the human and computer. Some examples are virtual or augmented reality

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(see VIRTUAL REALITY MODELING and AUGMENTED REALITY).

- The creation of new information visualization methods, which focus on the creation and implementation of mechanisms for displaying all kinds of information structures in interfaces, including numerical data (e.g., bar charts, plot charts, pie charts), combinations of such, and geographic (e.g., encoded maps) or time-oriented data (Aigner et al. 2007).
- The study of the incorporation of new advances in HCI to the engineering development process of software systems. This process usually includes specific contributions exploring the practice of engineering, making the process more user-oriented in all phases: from requirement elicitation phases, through user-centered design practices in development and programming of the components, to evaluation phases.
- The study of the implications of new paradigms of HCI in the evaluation and testing of any software product or information system. These approaches create models in different domains that conceptualize the tasks performed by the user with the software system, in order to determine how its adequacy, efficiency, or usability—quality attributes that assess how easy user interfaces are to use (Nielsen 1994)—can be evaluated, among other metrics.

All of these areas share the common goal of understanding the phenomenon of interaction between humans and computers, designing new methods, techniques, and technologies that increase the usability of all types of interfaces and components, and developing new ways to evaluate these developments with experimental studies with real users.

The future of HCI research

Some social factors are determining the current situation and the future roadmap in HCI research. First is the presence of information processing devices and embedded

systems in all aspects of life, such as home appliances and home automation applications, urban applications—creating Smart Cities—and changes in leisure and consumption habits. The network facilities of all these devices enable many of these embedded systems to be coordinated with each other as ubiquitous systems and communicate as a big network with the user. This is usually called the Internet of Things (IoT). The design and evaluation of the mechanisms of interaction with these systems present a major challenge in HCI research.

Especially relevant are social changes, such as relocation of work spaces and the explosion of social networks. These social changes have brought significant advances in some types of device (phones, tablets, smart glasses, etc.), generating new interaction requirements, such as the size reduction of interfaces, the need for adaptive interaction between user and multiplatform applications, collaborative interfaces with interactions that serve many users at once, and the productive incorporation of new developments that change input channels, such as voice-based interfaces and the inclusion of fingerprint analysis or other biometrics interactions in applications.

Another important factor has been the reduction of hardware costs and increased access to computing devices by the general public. This situation has led to new ways to interact with different devices that go beyond one dimension to explore the potentials of multisensory interaction. Good examples are current commercial devices that combine functionalities: bringing together in a single device audio, video, Internet browsing, access to TV channels, videogames, and so on. This phenomenon, coupled with advances in visual representation such as 3D technologies (see IMAGE-BASED 3D MODELING) and new techniques of information collection, allow the emergence of some qualitatively different interaction techniques, such as virtual reality, augmented reality interfaces (see VIRTUAL REALITY MODELING and AUGMENTED REALITY), and other immersive visualizations.

Finally, current trends in HCI argue for incorporating the knowledge of the users, their needs and abilities (see KNOWLEDGE AND INFERENCE), and using this information to replace generic systems with ones that adapt to the user's perception and understanding. Information modeling (see

INFORMATION MODELING), with its advances in semantic representation, allow user modeling as a part of the information system, improving the HCI.

All these lines in HCI research can contribute to create scientific advances that have enormous potential for solving research questions about the past, as well as the present, posed by humanities disciplines. Indeed, the application of advances in HCI research to the humanities forms a distinct subarea of the so-called digital humanities. Thus, humanities researchers, policy-makers, curators, editors, and heritage managers take into account HCI research for identifying, researching, and solving complex past and present cultural-related problems, due to their multilingual, heterogeneous diversity in origin and formats and volume in data, among other aspects of humanities information.

HCI research in humanities

Special mention should be made about the connections between HCI research and research in the humanities, particularly in archaeology-related disciplines (see DIGITAL HERITAGE). As previously mentioned, the widespread use of computational techniques for the resolution of questions in archaeological research about our past has encouraged the implementation of numerous HCI techniques and methods in these fields. Thus, HCI research constitutes an interesting area for archaeologists and other humanities professionals mainly due to (1) the HCI multidisciplinary character which constitutes a vast set of techniques and theoretical frameworks to represent, analyze, generate new knowledge, and disseminate humanities datasets and research results in a more human-intuitive way, for both researchers and professional colleagues and also for implementing new participatory ways in archaeology and humanities studies for all citizens; (2) some of the advances in HCI are currently used in discovering, analyzing, and testing new archaeological and humanistic hypotheses, for instance, helping archaeologists in detecting new archaeological places; and (3) the future of HCI aims at a greater human interaction with all kinds of devices in our daily lives, which makes

archaeology of the future necessarily a combined manual-machine work.

It is noteworthy that, although in most cases these techniques are applied to solve research questions in archaeology, sometimes this application has provided feedback, leading to scientific advances involving contributions in HCI research thanks to the challenges presented to HCI research by the humanistic domains. Good examples are studies of intrinsic characteristics of the interaction of professionals in the humanities, software patterns in humanities applications, and new algorithms that capture and visually represent archaeological objects such as vessels, stratigraphic sequences, and archaeological sites.

In addition, there are a good set of applications of HCI research in humanities fields that use all available HCI techniques and methods for the communication, dissemination, training, and participatory involvement of the general public in specific issues related to archaeology and other humanities disciplines (Morgan 2009). Thus, we can find HCI applications in museums (including completely virtual museums), in educational programs, and being applied in virtualization (Scopigno et al. 2011). The use of immersive environments, including the development of videogames and art structures, using HCI techniques are also good examples of this trend.

What is clear is that the HCI roadmap not only establishes a starting point for solving research questions about our past from a different approach, but also uses HCI applications to improve the dissemination of research results achieved in archaeology and related humanistic disciplines.

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Image-Based 3D Modeling

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Image-based three-dimensional (3D) modeling can be defined as the 3D reconstruction of a 3D space or object, such as an archaeological landscape, scene, or artifact, by using mathematical algorithms developed in computer vision science to extract using structure from motion (SfM) (Ullman 1979) algorithms and reconstruct using dense multiview stereo (MVS) algorithms (Szeliski 2011) the 3D shape and appearance of scenes or objects from 2D imagery.

Although these algorithms were developed in the 1970s (e.g., SfM), and image-based 3D reconstruction was applied in archaeology in the early 2000s, it is only in recent years that image-based 3D modeling techniques have become increasingly popular in archaeology and heritage studies. This is mainly a result of the democratization of the technology, with new hardware developments and implementation of SfM and MVS algorithms in low-cost and open source software packages. Recent applications include the image-based 3D modeling and analysis of archaeological landscapes, excavations, rock art, artifacts, and even underwater archaeology.

Procedure

To produce an image-based 3D model, one only needs a set of high-quality imagery. Ideally, each photograph is taken from a unique viewpoint, with sufficient overlap with the previous photo (i.e., 60–80% overlap) and each point in the scene is visible from at least three different images. The better the image acquisition strategy and the quality of the imagery, the better the resulting 3D model will be. Nevertheless, research has already shown that “old” imagery (e.g., historic aerial

photographs) can also be successfully used for image-based 3D modeling, given that the structure of the “old” imagery dataset corresponds more or less with the image-based 3D modeling parameters.

The first step in the image-based 3D modeling pipeline, and the most important as it determines the accuracy of the final 3D model, concerns the alignment of the photographs using SfM. SfM allows the reconstruction of the 3D scene or object by moving the camera to several positions around it. During the image alignment, (1) a 3D sparse point cloud is generated representing the geometry of the scene, (2) the relative orientation of the camera positions at the moment of image acquisition is determined, and (3) the internal camera parameters (focal length, principal point location, skew, radial, and tangential distortion coefficients) are computed. Using the computed camera position, one can opt to build a dense point cloud.

Second, the 3D geometry, or surface, of the scene or object is built using dense, multiview stereo- matching algorithms (e.g., Scharstein and Szeliski 2002; Seitz et al. 2006). The output is a polygonal mesh. Besides the computation of the 3D geometry, the color for each model vertex is also calculated and stored as an attribute. During the rendering of the model, these colors (which are an average of the corresponding pixel values from the source photos) are then interpolated for each polygon face, so that each face of the model is filled by a color gradient. When the number of polygons is large, this vertex color approach already provides a very good visual representation of the object's surface. The computation time largely depends on the resolution and the quantity of the used imagery and the level of detail wanted in the geometric model.

Finally, the texture of the object or scene, present in the photographs, can be mapped onto the 3D mesh. The texture atlas is calculated out of one or more source photographs. Each model vertex then stores its coordinate in this texture atlas. During rendering of the 3D object, these coordinates are used to map the texture image

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onto the 3D model surface. Since the original photographs are mapped onto the geometrical surface, it is possible to provide a very rich texture.

Once the 3D models are scaled or georeferenced, they can be used as an analytical tool to study the 3D shape of the archaeology. The 3D shape can be fully appreciated in a 3D environment (e.g., 3D geographic information system (GIS)), or downscaled to a 2.5D digital surface model (DSM) or a 2D orthophoto. The orthophoto is a geometrically correct 2D image with all the geometric characteristics of a map, while the DSM represents the topography of the uppermost surface of the orthophoto.

Considerations

As with all digital archaeology applications, although image-based 3D modeling has its problems and limitations, these are greatly surpassed by its possibilities. Moreover, computer technology is advancing so rapidly that the limitations are becoming mute (Zubrow 2006). Nevertheless, two limitations are worth discussing here.

First, image-based 3D modeling involves long processing times despite the amount of human time investment being limited to only a few minutes. To successfully produce 3D models, central processing unit/graphics processing unit (CPU/GPU) power and available memory are important. The better these settings, the faster the processing, the larger the number of photographs that can be handled, and the higher the point cloud accuracy and mesh density that can be achieved. Current average-priced computer systems are unable to deliver the highest possible data quality. However, there is no doubt that with new software developments and increasing computer power, the quality of the output, along with the usability and accessibility of the data, will rapidly improve in the (near) future.

Second, the success and accuracy of the image-based 3D modeling is affected by the feature richness of the recorded surface of the object or scene, and thus high-accuracy results are not always guaranteed. Archaeological artifacts in shiny or transparent materials (e.g., flint, glass,

or porcelain) are especially problematic to 3D reconstruct.

Archaeological applications

The application of image-based 3D modeling in various archaeological research projects since the turn of this century has proven that this technology provides detailed and accurate results—up to centimeter and even millimeter accuracies—and that it has the potential to be used worldwide, on a daily basis, at a large scale, and in different environments and conditions, in order to document a broad variety of archaeological landscapes, sites, features, contexts, and artifacts from different chronological eras. As opposed to range-based 3D reconstruction methods, image-based 3D modeling can be achieved with negligible equipment costs and with little to no overheads in the field.

Among other achievements—and in common with other 3D modeling techniques—the most important achievement of image-based 3D modeling is the documentation of the 3D shape of the archaeology, and the possibility it offers to analyze our archaeological data in 3D.

The most popular (and arguably most successful) application of image-based 3D modeling in the field of archaeology can be found in the practice of documenting archaeological excavations. The entire archaeological excavation can be recorded as a 3D space, and the 3D shape of the archaeology can be fully explored and analyzed. With the high accuracy of the methodology, which is frequently more accurate than is probably needed on an archaeological excavation, and with the information about the texture, color, and appearance of the archaeology, present in the photographs mapped onto the 3D model, the 3D modeling results in an accurate, photorealistic 3D reconstruction of the excavation that makes it almost possible to experience and revisit the excavation in a digital environment. The digital environment can be a 2D or 3D GIS that allows full integration of the 3D data with other aspects of the excavation in one spatial environment. If processed during the excavation, the 3D models can be used together with other means of documentation to monitor the field activities

and to plan excavation strategies. Besides the documentation of the 3D shape of the archaeology, another key aspect here is the possibility to record an excavation in a more objective way than with analog methods. Although an excavation can never be fully objective, and, just like with traditional recording techniques, it is the archaeologist who decides on what to excavate and what to document, a more objective documentation of the excavation can be achieved with image-based 3D modeling. The result of the documentation process is, however, a record of the archaeology as it is there, with its 3D shape, its color, and its appearance, and without the interference of the archaeologist's personal interpretation. After the generation of the 3D model, the archaeologist's observations, descriptions, and interpretations are/can be added to the 3D model (as a separate layer). As an important consequence, the 3D model can be (re)viewed, by the excavator(s) or by others, with the archaeologist's interpretation, while an analog recording always represents the archaeologist's personal interpretations. Although this objectivity is a very important achievement for archaeological field research, image-based 3D models cannot be seen as a substitute for traditional descriptive and/or interpretative means of excavation documentation (e.g., drawings). In fact, both methods should be used in a complementary fashion as they provide different "views" on the same subject, both aiding the understanding of the archaeology.

Image-based 3D modeling can be successfully applied on scales much larger than the individual site, encompassing the archaeological landscape. However, unlike light detection and ranging (LiDAR), image-based 3D modeling can only be successfully applied in open landscapes where a vegetation cover is absent. In these open landscapes it allows the 3D modeling of the topographical characteristics of the terrain and detailed analysis of the layout of an archaeological landscape. On this landscape level, the image acquisition usually happens with balloons, kites, or helikites, and more recently with unmanned aerial vehicles (UAVs) or drones. These UAVs hold great potential for archaeology (e.g., to collect aerial images, to map archaeology, or to protect and monitor endangered sites), and they are very suitable to extend the scale of image acquisition for image-based 3D modeling.

With UAVs, larger areas can be covered, and 3D modeled in shorter periods, making UAV-based image-based 3D modeling suitable not only for mapping archaeological sites and landscapes, but also to monitor endangered sites (e.g., modeling of erosion or damage over time).

Similarly, old historic imagery, like military photographs, if suitable for image-based 3D modeling, can be used for the 3D reconstruction of past landscapes. These data are useful to study the evolution of archaeological landscapes through time (e.g., preservation, erosion) or to reconstruct archaeological landscapes that are lost forever (e.g., urbanized landscapes). In this light, image-based 3D modeling has also been successfully applied in the 3D reconstruction of World Heritage Sites, damaged or destroyed in military conflicts (e.g., the Great Buddha of Bamiyan; Grün, Remondino, and Zhang 2004). In these cases, the reconstructions are often made by using tourist photographs. Also, built heritage (or architecture) has frequently been the subject of image-based 3D modeling. Here, the 3D models are made to document and analyze the state of preservation, to detect damage, to model future decay, or to study the construction and architecture of the built heritage.

Image-based 3D modeling has also proven useful in the documentation and study of rock art, both at the level of the detailed study of the individual panel and at the larger landscape level. It also provides a digital copy—a digital means of preservation of this fragile heritage. Probably the most challenging application of image-based 3D modeling in the field of archaeology can be found in underwater archaeology. Its successful application in this difficult underwater environment is another example of the flexibility of use and the great potential of this technology.

On a smaller scale, but no less important, is the image-based 3D modeling of artifacts. While nothing compares to the real artifact, digital 3D copies have proven to be a highly valuable alternative when one is away from the original object, or when it is inaccessible for other reasons. Also, they allow new, simple-to-more-complex metric analyses, allowing detailed shape analysis of the artifacts. Another major advantage of possessing digital copies of artifacts lies in the opportunity to set up a digital reference collection of different types of artifacts. A digital reference collection

can not only be used by researchers as a tool for comparing, identifying, and interpreting artifacts, but also holds great educational potential. Digital 3D reference collections of artifacts can become the new “reference books” for artifact typology, determination, and interpretation, a role currently fulfilled by illustrated textbooks. One can only imagine the research possibilities when entire archaeological excavations, depots, museum, and collections will be available through a 3D library.

Image-based 3D modeling provides an excellent tool for the 3D documentation of archaeology, from the artifact to the landscape level, opening new doors to multidimensional analysis and digital preservation of this heritage.

SEE ALSO: Authenticity in VRM; Computational Photography; Digital Photogrammetry; Multi-View Stereo; Structure from Motion

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Imaging

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Imaging is the visual representation or reproduction of an object. Imaging is the technique or practice of creating images of otherwise invisible aspects of an object. This includes detecting archaeological remains on the landscape from the air or space, or with remote sensing techniques, visualizing the chemical compositions of archaeological objects, or the examination of objects with noninvasive techniques.

The field of imaging techniques used in archaeology and heritage studies is widespread, including chemical (e.g., multispectral and hyperspectral imaging, neuron imaging), digital (e.g., reflection transformation imaging, three-dimensional (3D) imaging), geophysical (e.g., electromagnetic techniques, ground-penetrating radar, imaging spectroscopy), medical/molecular (e.g., computed tomography (CT) imaging, magnetic resonance imaging (MRI), terahertz (THz) imaging), and thermographic (e.g. infrared imaging, near-infrared imaging) imaging.

The availability of digital tools for the documentation of world heritage has increased exponentially in the decades since the 1960s. Equipment costs have come down while, simultaneously, the imaging processing speed has gone up. Tools and techniques, especially visualization techniques which were once reserved for the best-funded projects, have been adopted by a broader segment of the archaeological community.

Imaging methods use measurement data to visually represent archaeological objects in order to detect and delimit their characteristics. Measurement data, or information derived from the measurements, is spatially resolved and is made visible through the assignment of brightness or color values. Imaging methods are applied in almost every natural scientific field, including

medicine, archaeology, material inspection, and remote sensing, to name a few.

The word “imaging” was already in use as early as the fourteenth century by the German mystic Heinrich Seuse in his “Vita” where he uses the terms “*bildgebender wise*” (imaging manner) and “*bildgebender glichnus*” (imaging parable) (Seuse 1907, 3.3, 191.1).

The oldest and simplest imaging tool is the camera obscura or the pinhole camera (Renner 1999). It was in use at the end of the thirteenth century by astronomers for the observation of sunspots. Telescopes and microscopes are other imaging tools and these were developed around 1600.

The discovery of X-rays, development of the computer, and invention of the digital still camera allowed for the broad use of imaging technologies. These started in the field of medicine during the 1970s and rapidly spread to other scientific disciplines.

X-rays were first used in 1898 by the archaeologist Sir Flinders Petrie to image the inside of an Egyptian mummy, just three years after their discovery by Wilhelm Roentgen. Petrie was followed by Elliot Smith and Howard Carter in 1904 (Hughes 2011, 57). Medical X-ray CT scanners became available in the early 1970s and were a gigantic leap in diagnostic imaging. With the CT scanner, it was the first time that 3D images of the body could be produced. The first CT scan of a mummy was performed in 1977 by Derek Harwood-Nash in Toronto, Canada (Harwood-Nash 1979). CT imaging is also used in the study of clay and ceramic archaeological objects, metal works like coins, and other organic remains.

MRI was invented by Paul C. Lauterbur in 1971. MRI is not frequently used in archaeological studies because the scanned object needs to have significant moisture content, which is generally not the case for archaeological artifacts (Hughes 2011, 60). In 2009, THz imaging was performed on parts of a mummy in conjunction with CT and was found to provide more soft tissue information than CT, although at lower spatial resolution.

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The 1960s saw the beginning of archaeological computing and processual ways of thinking. Invention of the microprocessor in 1971 and the subsequent rapid development of microprocessors have been breath-taking and are encapsulated within the generally acknowledged Moore's Law. In the late 1980s and 1990s, the development of graphics, visualization, multimedia, and integrated software products also paved the way for imaging technologies.

Since its very first applications, photography has striven for the accurate reproduction of reality. The first photograph ever produced was in 1826 by the Frenchman Joseph Nicéphore Niépce. The first digital image was produced in 1920, by the Bartlane cable picture transmission system. British inventors Harry G. Bartholomew and Maynard D. McFarlane developed this method. Steven Sasson, an engineer at Eastman Kodak, invented and built the first electronic camera using a charge-coupled device image sensor in 1975. It was the mid-1980s before electronic cameras began to be introduced to the commercial market. Storage was the problem that needed to be overcome for widespread adoption. Some of the first digital cameras recorded images to cassette tapes, and even into the 1980s most used floppy disks. The first digital cameras for the consumer-level market that worked with a home computer via a serial cable were produced in the mid-1990s. In recent years, the quality and the resolution of digital cameras and digital video

cameras has reached a level that they can be used for special digital imaging projects such as airborne photography and satellite imaging.

SEE ALSO: Aerial Photography; Airborne Laser Scanning and Lidar; Airborne Remote Sensing; Computational Photography; Computed Tomography; Electrical Resistivity; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Infrared Reflectance Spectroscopy; IR Thermography; Satellite Hyperspectral and Multispectral Imaging; Terahertz Imaging in Conservation; Underwater Three-Dimensional Laser Imaging; Visualization of Ground-Penetrating Radar Data; X-Ray Tomography

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Information Modeling

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Context and overview

Science uses models for multiple purposes, such as describing, explaining, and communicating things. The concept of model is old, dating back to at least the seventeenth century, accompanying the prelude of modern science. Since then, a model has been considered to be an artifact constructed to represent something in a meaningful way. For example, a cardboard replica of a planned house development created by an architect in order to study and decide on the lighting and overall appearance is a model; similarly, a Harris matrix that an archaeologist draws on paper in order to document, communicate, and reason about the stratigraphy of a place is also a model. The notion of model as representation has several consequences. First, a model represents something. For example, a map represents a portion of the territory, or a Harris matrix represents a stratigraphic sequence. Second, a model provides a simplified view of the represented subject. For example, the lines and shapes on a map are much simpler than the real territory, and the boxes and connectors on a Harris matrix capture vital information about relative location of each stratigraphic unit, but discard other aspects such as their size or chemical composition. In this regard, the *purpose* when creating a model determines what details are retained and which ones are discarded; for this reason, two models of the same thing can be very different if they pursue different goals. For example, the models of the human body that are often employed by doctors and anthropologists are quite different. Finally, a model allows us to reason on the representation, and then apply the conclusions to the modeled subject. For example, measurements carried

out on a map are expected to be valid on the terrain.

An information model is a model that is composed of information, rather than cardboard or ink on paper. Information models, like any other models, represent something by simplifying it and allow us to reason about it by looking at this simplified view, and then apply the results to the original thing. However, since information models are made of information, it is often difficult to convey the model in a straightforward manner, because information, as such, is not visible but abstract. For this reason, information models are usually depicted on paper or a computer screen in order to be useful. For example, the collection of deposits, interfaces, and other strata at a particular site, when observed by an archaeologist, can be conceptualized as a network of interlinked stratigraphic units in the archaeologist's mind. Then, they can draw a sketch on their notepad representing these ideas. There are two representation processes going on here: from the physical entities observed in the world to the network of stratigraphic units and links in the archaeologist's mind, and from these to a collection of boxes and lines sketched on a sheet of paper. Both the first and last entities in the chain, namely the actual strata and the ink on paper, comprise physical things. The intermediate entity, namely the conceptualization in the archaeologist's mind, is an information model.

Information models are more abstract than data and less abstract than knowledge, according to Ackoff's hierarchy (Ackoff 1989). Data are usually understood as being composed of simple and uninterpreted quantities or qualities such as numbers, texts, or images. Information builds on data by adding a sender and a meaning to be conveyed; in other words, information is about telling others about things by using data and for a particular purpose, and for this reason it involves a particular interpretation. Knowledge, in turn, is related to true justified beliefs, which are constructed on information and usually conveyed through it. In this context, information models work by capturing and conveying the necessary

data to the right people in order to generate new, or revise existing, knowledge (see KNOWLEDGE AND INFERENCE).

Information models can be useful in relation to five major purposes. First, they can help people *explore* areas of the world that are not well understood. For example, you can try to represent the same archaeological evidence by selecting different details to capture, so that you try various approaches to describe the same reality and see how well each one works. Second, information models are useful to *document* things or phenomena for later reference. Usually, archaeological works such as excavations entail the complete destruction of the things being studied and, for this reason, having a good model of these things is crucial. Third, models are useful to *communicate* information to others. For example, an information model can be very useful when archaeologists work together with specialists from other disciplines such as anthropologists or architects, because it helps bridge the gap between the different mindsets and working styles of the different disciplines, and establishes a lingua franca that everyone can understand. Fourth, models are useful to help people *design* tools and techniques for their work. For example, a good information model is an excellent basis on which to develop field survey forms or database structures to store and manage the recorded data. Finally, models are useful to make information and tools *interoperate* with others. People naturally tend to work in a manner that is best adjusted to the task at hand; however, they often want to interchange information with others, compare results to multiple sources, or even integrate information into larger corpora. For this to happen, information needs to be clearly and unambiguously expressed, as it usually is when employing an information model.

What information models can express

Information models can express almost anything about anything. They accomplish this by addressing very abstract kinds of statements that can be made in natural language. First, information models can express *existence*, that is to say, they can state that something exists. For example, in “There are five Iron Age sites in this region,” existence of five sites is being stated. Second,

they can express *identity*, that is, whether two things are the same or not. For example, in “This place is where ore was extracted by the people of that settlement,” a statement is being made that “this place” and “where ore was extracted” are the same thing. Third, information models can express *predication* or, in other words, the assignment of a property or role to an entity. For example, in “This site covers 8,500 square meters,” the value of *8,500 square meters* is being assigned to the site’s *surface area* property. Fourth, information models can express *classification*, that is, they can assign a category to an entity. For example, in “This is a fragment of a bell beaker,” something is being classified as a fragment of a particular kind of vessel (see ARCHAEOLOGICAL CLASSIFICATION). Finally, they can express *subsumption* or, in other words, the fact that some categories subsume or encompass other categories. For example, in “A hillfort is a kind of settlement,” the *settlement* category is being stated to subsume or encompass *hillfort*.

In this manner, an information model is a collection of information elements and relationships between them, so that its content and structure represent some relevant portion of the world.

Technical aspects

Natural language allows us to express almost anything, but it usually involves a large degree of ambiguity and underspecification. Although natural language is, and will certainly remain, a crucial mechanism for representation in science, information models can do better in specific situations that require a higher degree of expressive accuracy. In fact, information models are usually constructed by using a particular *modeling language*, that is, a set of rules and conventions that determine how things are expressed. A modeling language, like a natural language, involves a lexicon, grammar, and some semantics. The lexicon is the set of “words” or basic language units that people can use. For example, when constructing a Harris matrix, two kinds of language units are often used: stratigraphic units and links. The grammar comprises a set of rules that must be obeyed when putting lexicon elements together in order to compose meaningful “sentences.” For example, in a Harris matrix, one stratigraphic

unit can be connected to another through a link, but links cannot be connected to other links. The semantics of the modeling language is the collection of relationships between the mentioned “words” in the lexicon and the things in the world that they refer to. In the case of Harris matrices, semantics tells us that labeled boxes correspond to specific deposits, interfaces, or other strata, and links correspond to specific sequencing situations between them.

Modeling languages and, as a consequence, information models allow people to represent the world according to two different viewpoints, by focusing on either entities or categories. The first one refers to the specific entities that can be observed or imagined. For example, an archaeologist may create an information model describing the set of ramparts, ditches, walls, and other structures found during the excavation of an Iron Age hillfort. This model would be describing that specific hillfort, and each element in the model would correspond to a specific rampart, ditch, or wall in the world. Model elements that stand for specific entities in the world are called *instances*. However, there is a second way to represent the world, namely, in terms of the categories of things that are observed or expected, rather than the very specific things themselves. For example, an archaeologist planning to study how people living in different hillforts exploited their immediate environment and traded between them may create a model that describes the different activities that are expected to be found, such as mining or fishing, and how these activities can be related to hillforts. This model would not be describing any particular hillfort or activity, but the fact that, in general, activities of different kinds can be associated with hillforts and these, in turn, can be related to other hillforts in relation to activities. In other words, this model would be describing the world in terms of categories (*hillfort*, *fishing activity*, *mining activity*, etc.) and connections between them. Model elements that stand for specific categories are called *types*.

Instance models are useful to describe a specific thing or phenomenon, such as a particular site, feature, society, or cultural process. Type models, on the other hand, are useful to describe general patterns that are observed or expected, such as the ways in which features and finds are

related, what finds appear where, what processes occurred in what places and when, or how people enjoy visiting site museums. Type models, being based on categories rather than specific entities, involve a larger degree of subjectivity, and may be more difficult to develop. However, and since they are much more encompassing than instance models, they can potentially be useful to many more people and in multiple situations.

Furthermore, instance and type models are strongly connected through *conformance*. When an instance model is created to describe particular entities in the world, the author can state, as part of the model, how each of the represented entities is categorized. In this manner, a connection is established between the instance model being created and a previously existing type model that describes what categories of things are expected. For example, when describing a particular lithic artifact as part of the instance model, information may be included that states that the thing being described is classified as a *LithicArtifact*. In order for conformance to work, and for these data to be meaningful, the *LithicArtifact* category must be present in a pre-existing type model. In a situation like this, it is said that the instance model being created conforms to the mentioned type model. Often, type models are created first, as a rough approximation to what kinds of things are expected to exist in a particular place or situation, and then conforming instance models are constructed to describe specific explorations or perspectives on the place or situation. For example, a research group may agree on a type model describing the major categories of things in the archaeological record that they usually work with, such as *Place*, *Site*, *Artifact*, or *Hillfort*. Then, each project or individual archaeological action creates an instance model that conforms to this type model in order to document and communicate what was found.

Finally, information models, being made of information, are invisible, so they must be represented visually in order to be shared or discussed. For this purpose, a *graphical notation* is often employed that establishes some rules on how to depict each type of model element. When represented graphically, information models usually take the form of diagrams composed of boxes, lines, and texts.

History of information modeling

As practiced today, information modeling in archaeology is based on two different streams of research that took place over the last few decades: conceptual modeling and ontology engineering. These two fields have been converging for some time and in many respects overlap greatly. Conceptual modeling appeared within the software engineering discipline in the 1980s as a manner to represent the structural and functional requirements of stakeholders in terms of concepts, as well as the software systems to be developed from these requirements. The major aim of conceptual modeling was to be highly expressive and as accurate as possible in its descriptions, and a large body of work was developed over the 1990s and 2000s with this purpose in mind. Languages such as unified modeling language (UML), initiatives such as the Object Management Group's (OMG) model-driven architecture (MDA), and toolsets such as Eclipse helped further this field. Today, conceptual modeling is pervasive in the software engineering industry. However, conceptual modeling and software are linked only for historical reasons, and an increasing number of projects are employing conceptual modeling in areas different to software such as business organization and genomics.

In parallel, ontology engineering emerged within the artificial intelligence community starting back in the 1970s. The major aim of artificial intelligence was to create machines that could think like humans; for this purpose, some authors focused on studying how portions of reality can be represented inside a computer so that automatic reasoning can be carried out on them (see ARTIFICIAL INTELLIGENCE). As opposed to conceptual modeling, the major focus here was not expressivity or accuracy, but allowing computers to use the represented information to perform automatic reasoning. Significant innovations were made over the 1990s and 2000s, including technologies such as CycL, a computer language based on first-order logic that could manipulate a "knowledge base" and carry out reasoning on its contents. Eventually, models constructed under this line of work were named "ontologies," in reference to the branch of philosophy that studies what things exist and how. Since then, ontology engineering (see

SEMANTIC WEB AND ONTOLOGIES) has been an active area of research, especially in the context of the so-called semantic web. The semantic web is the idea, pioneered by World Wide Web inventor Tim Berners-Lee, that the information available on the web should be processable by machines in addition to humans. In this context, having "ontologies" that describe specific realms of reality in a machine-oriented manner is crucial. The World Wide Web Consortium (W3C) has developed this idea into technologies such as linked open data, the Simple Knowledge Organization System (SKOS), and Web Ontology Language (OWL) (see SEMANTIC WEB AND ONTOLOGIES).

Conceptual modeling and ontology engineering, although coming from different backgrounds, pursue very similar goals. Recently, some authors have argued that ontologies are in fact a particular kind of conceptual model, and that both can be easily aligned and reconciled. Also, recent works in conceptual modeling have emphasized an ontological approach, and recent works in ontology engineering have moved closer to conceptual modeling. In this manner, information modeling in archaeology can draw from both fields without major issues.

Current and future developments

Under the umbrella of the digital humanities and, in particular, digital archaeology, many research lines are actively working on archaeological information modeling. One of the most active areas relates to the creation of ontologies (or information models) of the archaeological record and associated things. A good example is ISO 21127 (ISO 2014), also known as the CIDOC Conceptual Reference Model (CRM). This is a collections-oriented type model that describes everything related to heritage areas, which has been standardized by ISO. CIDOC CRM-English Heritage (EH) is an extension to the original CIDOC CRM that addresses archaeological processes. A second relevant example is the Cultural Heritage Abstract Reference Model (CHARM) (Incipit 2016a), a type model that also addresses heritage as a whole, but which is based on an extensible framework so that adjusted particular models can be created for specific projects. Using

CHARM, different projects or organizations can employ different conceptualizations of the archaeological record (and, as a consequence, different models), but still maintain the necessary interoperability between them.

A second area of active research is that of the development of specific tools and online services based on archaeological information models. Large infrastructure projects such as Europeana or Advanced Research Infrastructure for Archaeological Dataset Networking in Europe (ARI-ADNE) are providing aggregated datasets that can be queried online and integrated with others.

Finally, a challenging and emerging area of research is that of improving the representation process itself. Archaeology, like other disciplines in the humanities and social sciences, involves “soft” issues such as subjectivity, temporality, and vagueness that are rarely considered by the engineering-oriented disciplines from which information modeling has emerged. To improve the existing modeling mechanisms with new features, research is being carried out in the area of modeling languages. A significant example is ConML (Incipit 2016b), a conceptual modeling language that incorporates explicit temporality and subjectivity management as well as some support for ontological and epistemic vagueness.

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Infrared Reflectance Spectroscopy

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Introduction

Infrared spectroscopy is a field of science exploring the interaction of infrared radiation with the matter being investigated. The infrared radiation itself is a part of the electromagnetic spectrum located between visible light and microwaves, covering wavelengths between 700 nm and 1 mm. Infrared spectroscopy has proven its greatest applicability in several scientific fields, including archaeology (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)). This technique permits chemical composition assessment, the identification of materials, and authentication and provenance recognition, among other capabilities. The measurement is rapid, nondestructive, and highly informative. If properly configured, infrared spectra include both qualitative and quantitative information, assessed from any kind of sample (organic, inorganic) in any state (liquid, gaseous, solid), and presented in a small amount (milligrams) (Stuart 2004).

Theoretical background

The infrared radiation emitted into the sample can be transmitted, absorbed, reflected, and/or scattered. Absorption occurs when a specific molecule exposed to such radiation excites to vibration in covalent bonds, matching the radiation frequency and the natural vibrational frequency of the molecule. In principle, only molecules with a change in the dipole momentum absorb infrared, thus only specific functional

groups are detectable in a spectrum (such as amides in the silk proteins, phosphate in bones, hydroxyl groups in cellulose, etc.). The pattern of absorption is highly selective and depends on the molecular configuration of the measured matrix as well as on the properties of the stimuli (radiation) applied. The scatter is not related to the chemical composition of the sample, but to the physical arrangement of molecules. The pattern of the light scatter relies, therefore, on particular properties such as density, crystallinity, and size of particles.

The overall infrared band is subdivided into three regions corresponding to the near-infrared (NIR), mid-infrared (IR) and far-infrared (FIR). The IR region is sectioned into short-wavelength infrared (SWIR), mid-wavelength infrared (MWIR), and long-wavelength infrared (LWIR). Diverse characteristics of matter can be assessed when measuring spectra in each region, with the functional group region and fingerprint region included in the mid-infrared range. Combination bands and overtones of fundamental vibrations are located within the near-infrared.

The light transmitted through the sample is analyzed with conventional infrared spectroscopy, in contrast to reflectance spectroscopy when only part of the light reflected from the sample surface is assessed. Three modes of reflection occur in the majority of materials: specular, diffuse, and attenuated reflectance. In practice, all three of these take place simultaneously, although with different contributions (Khoshhesab 2012).

Attenuated total reflectance (ATR) occurs when a beam of radiation passes from an optically denser medium (high refractive index) into a less-dense medium possessing a lower refractive index. The total internal reflection of the light at the interface zone creates an “evanescent wave” that penetrates the subsurface of the sample. Crystals with a high refractive index and excellent infrared light transmittance, such as diamond, zinc selenide (ZnSe), or germanium (Ge), are usually used as internal reflection elements. The evanescent wave is absorbed (attenuated) when the sample is placed in close

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contact with the crystal. The ATR technique is an optimal solution for assessing thick samples strongly absorbing infrared. It provides similar spectra to that of transmittance, with the exception of slightly higher absorption at longer wavelengths.

Specular reflectance occurs when the major part of the light is reflected at the same angle (to the normal) as incident radiation. The specular reflectance measurement provides excellent qualitative data and may be used for analysis of organic and inorganic samples having large, flat, reflective surfaces. In any case, some of the energy that passes through the surface layer is absorbed into the bulk of the sample, and then reflects from a substrate below. It is especially evident in the case of measuring thin samples or films placed on a mirror, when combined reflection and transmission become transreflectance. The reflectance/transreflectance spectra differ, therefore, from those recorded in a pure transmission. The Kramers-Kronig transformation is used to remove effects of dispersion and to permit qualitative comparison of spectra.

The infrared radiation reflected from rough surfaces, defined as “Kubelka–Munk” reflection, is analyzed with *diffuse reflectance spectroscopy* (DRS). This technique is used for the characterization of solid samples or powders (both organic and inorganic) having a coarse surface such as textiles, wood, bones, or paper. Particle size, homogeneity, and packing density of powdered samples highly influence the quality of spectrum; therefore special attention should be directed to sample preparation and presentation. The scattering phenomenon is more pronounced at shorter wavelengths. Thus, diffuse reflectance measurement in the near infrared range (DRIFTS) is most commonly utilized. Similarly, the infrared penetration depth depends on the light wavelength and optical density of the bulk material, varying between fractions of micrometers to a few millimeters.

Instrumentation suitable for archaeology

Infrared spectroscopy is a relatively well-established technology, and dedicated spectrometers have been commercially available since the 1940s. Today, several options for infrared

spectra acquisition exist in all ranges, with the majority of instruments tuned to sense near- and mid-infrared frequencies. The most important practical considerations when selecting an optimal spectrometer are to define the expected rigidity of the sensor (dedicated to laboratory or in-field applications), required spectra range, resolution, sensitivity, and scanning time.

Fourier transform (FT-IR and FT-NIR) spectroscopy provides superior quality of spectra in a relatively short measurement time. However, the application of these instruments is usually limited to the laboratory environment because the optics implemented (e.g., interferometers) are very sensitive to mechanical vibration. The raw result of measurement is a time-resolved interferogram, converted into a spectrum with a fast Fourier transform (FT). FT spectrophotometers operating in the NIR range are frequently equipped with fiberoptics or an integration sphere.

Dispersive fixed grating diode array (DA) and linear variable filter (LVF) spectrophotometers have small size, a lightweight/compact design, and do not contain moving parts. In combination with a short scanning time, both techniques are alternative solutions for in-field measurements. The drawbacks are the limited spectral range, sensitivity, and lower resolution when compared with FT spectrophotometers.

Hyperspectral imaging (HI) (see MULTI-SPECTRAL AND HYPERSPECTRAL IMAGING OF ARTWORKS) allows the acquisition of spatially resolved spectra, and this is advantageous for the characterization of heterogenic materials or chemical mapping (see CHEMICAL MAPPING) of complex sample surfaces. As an alternative, multispectral imaging (MI) is used if fewer than ten images at diverse spectral bands are acquired at once. Placing the HI or MI cameras on drones or aeroplanes allows the spectral imaging of large areas in a relatively short time without any disturbance of investigated artifacts or archaeological sites (see SATELLITE HYPERSPECTRAL AND MULTISPECTRAL IMAGING). Hyperspectral imaging of archaeological objects might also be an alternative during artifact assessment, since every pixel contains spatially resolved chemical information.

Result of measurement

The spectrum is the usual result of the infrared measurement. It corresponds to an array of numbers in which the amount of light absorbed/reflected/transmitted is associated with the incident light wavelength. The spectrum

can be plotted on a graph where the ordinate corresponds to the absorbance and the abscissa to the wavenumber (cm^{-1}) or light wavelength (nm). Depending on the measurement range, a spectrum might include information related to the fundamental vibrations (IR), overtones (NIR), or combination bands (NIR). The most

Table 1 Properties of diverse archaeological objects assessed with reflectance infrared spectroscopy.

<i>Type of object</i>	<i>Property</i>
Bones, ashes	Distinguish unburned from burned bone Cremation temperature and duration Diagenesis
Food residues	Detection of food remains and organic components in sediments Identification of di- and triglycerides from meat fats, nut oils, maize, and a variety of plants
Textiles	Recognition of nature of fibers and dye types
Wood	Prediction of cellulose and lignin content Assessment of decay type Estimation of waterlogging conditions
Paper and parchment	Evaluation of preservation state Type and provenance Ink composition
Pottery, ceramics	Identification of traces of the mineralogical composition present in ceramics, pastes, temper particles, binders, glazes, slips, paints, and pigments Identification of crystalline minerals and pseudo-amorphous fired-clay Clay provenance Firing temperature
Porcelain	Pigment and glaze composition Firing temperature and conditions Analysis of tints and shades of the blue coloration Oxidation states and relative amounts of cobalt, iron and manganese
Frescos	In-situ pigment identification Discovery of discolored/lower layers
Inks, binders, coatings, and paintings	Differentiating between the classes of natural organic materials for conservation purposes Actual decrease of the components on leaching of the paint film Loss of carboxylic acids and triglyceride ester linkages Recognition of ink types Decisions regarding conservation treatment
Gemstones	Recognition of mineral type Sourcing and provenance
Amber	Distinguish variety and provenance
Sediments and deposits	Identification of type of deposits Susceptibility to severe diagenetic alteration
Stone tools	Identification of animal micro-residues on stone tools Chemical signature

important limitation of infrared spectroscopy is the very complex nature of the raw spectra and consequent necessity for use of sophisticated mathematical methods for data mining (see *MULTIVARIATE ANALYSIS*). Chemometrics, the science of extracting information from the chemical system, is most frequently used for interpretation, exploration, classification, and regression analysis of the infrared spectral data.

Visual interpretation is most effective in the case of IR spectra, especially within the fingerprint region ($650\text{--}1750\text{ cm}^{-1}$). Several existing band assessment tables may assist interpretation; however, development of custom knowledge bases is indispensable in most real cases of archaeological studies. This is because many archaeological materials are composites of several constituents (e.g., oils, resins, fats), and so their spectral signal is a complex superposition of individual components. Furthermore, several deterioration processes (see *DETERIORATION*) take place during artifact deposition as well as when post-excavation and/or post-depositional contamination occurs.

Pre-processing of infrared spectra is frequently used to minimize variability within the signals and to assist the data interpretation. Averaging, smoothing, derivatives, normalization, baseline, or scatter correction are routine, and are the protocols most ordinarily implemented.

Basic exploratory analysis allows recognition of a hidden structure within large datasets. Principal component analysis (PCA) or cluster analysis (CA) allow visualization of natural clustering of the spectral data. The infrared spectra are a highly useful source for quantitative analysis of measured materials. Partial least squares (PLS), multiple linear regression (MLR) and principal components regression (PCR) are methods commonly used for numerical modeling and prediction (see *PREDICTIVE MODELING*). In any case, the model is assumed to be reliable only after a proper validation procedure. The independent test set validation is considered as superior and should be applied for testing of model robustness.

Application examples in archaeology

Proper spectroscopic data analysis allows the determination of an artifact's conservation state, its transformation in time, as well as deterioration rate caused by biotic and abiotic degradation processes that include decay, weathering, water-logging, thermal degradation, and crystallinity change (Margalis 2014). Several successful applications of infrared reflectance spectroscopy within archaeology are reported in the literature (Table 1), covering various types of objects, measured both in the field and in the lab, during excavation, intervention, and/or conservation.

Limitations of infrared spectroscopy

While possessing several advantages, infrared spectroscopy also has important limitations. Not all of the chemical-physical properties of the material can be directly assessed with infrared techniques. For this reason, it is extremely important to ensure the proper preparation of the calibration and validation datasets covering the whole range of the measured property variation. The process for the correct implementation of spectroscopy is very complex, starting from appropriate problem definition, experimental design, descriptive sampling, instrument selection and configuration, and ending with trustworthy chemometric analysis. Once developed, models need to be constantly validated and updated (Sandak, Sandak, and Meder 2016).

SEE ALSO: Chemical Mapping; Deterioration; Infrared Absorption Spectroscopy (IR, FTIR, DRIFT, ATR); Multispectral and Hyperspectral Imaging of Artworks; Multivariate Analysis; Predictive Modeling; Satellite Hyperspectral and Multispectral Imaging

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Isovist Analysis

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Visibility can be defined as the extent to which the spaces between walls and obstacles are visible to one another in excavated towns or buildings. Since the millennium, the space syntax method, developed by Bill Hillier and colleagues at University College London, has been applied to archaeological studies in order to explore this property. This method consists of calculating the various degrees of visibility of the built environments' public spaces and spaces inside buildings.

For analyzing built environments, space syntax consists of four things. First, it gives a *concise definition* of urban space. Second, space syntax is a family of techniques for *analyzing* built environments as the networks of space formed by the placing, grouping, and orientation of buildings. Third, in the field of archaeology, space syntax offers a set of techniques for *observing* how these networks of space relate to functional patterns such as the dispersal of functions, area differentiation, and the location of various identified artifacts. Fourth, based on empirical results, space syntax is a set of *theories* about how urban space networks relate in general to the social, economic, and cognitive factors that shape them and are affected by them. Underlying this is the *theory of the natural movement economic process* which states that the spatial configuration of the built environment influences the movement pattern from everywhere to everywhere else and the location pattern of economic-related activities (Hillier et al. 1993), and the techniques have been applied to a large number of cities in different parts of the world. In this way, a substantial database now exists of cities that have been studied at some level using space syntax (Hillier et al. 2007).

The space syntax method offers three basic elements for analyzing visibility: convex space, isovist field, and axial line (Figure 1). The main

assumptions behind these elements are that (1) human beings move according to axial sightlines; (2) they interact in convex spaces; and (3) they see changeable panoptical views when moving around in the built environment.

A *convex space* is defined as a space such that "all points within that space can be joined to all others without passing outside the boundary of the space" (Hillier 1988, 68). It is mostly used for studying the occupation of various functions and place-bound human activities such as standing and sitting. Convex maps are used for analyzing buildings and the public spaces between a group of buildings in neighborhoods or smaller villages. More recently, point depth and all-lines analyses have replaced the convex space analysis (see below).

An *isovist field* represents the panoptical view a person has from a given point in an urban space. It is used for orientation or way-finding in the urban fabric. According to Benedikt, an isovist is "the set of all points visible from a given vantage point in space and with respect to an environment" (Benedikt 1979, 47). It visualizes the panoptical view from the viewer from a particular standing point in a built environment, where borders are defined by walls and freestanding objects such as trees, bushes, and statues. When moving around, the shape and size of the isovist change. It is thus possible to visualize the sequence of scenes or panoptical view arrows from particular points along the movement routes.

The 180-degree isovist field shows the panoptical view when entering a place, while the 360-degree isovist field shows the panoptical view when turning around on the spot. Consider person A entering a place, as shown in Figure 2. A is a visitor and wants to have an overview over the area. Behind a building, person B is hiding from person A. An isovist field of 180 degrees is made for visualizing A's direct view. Person B has to know that A cannot see him or her. Therefore an isovist field of 360 degrees is made from B's position. The isovist field for person A is larger than that for person B, because person A is standing at a place with a large overview. Person B is

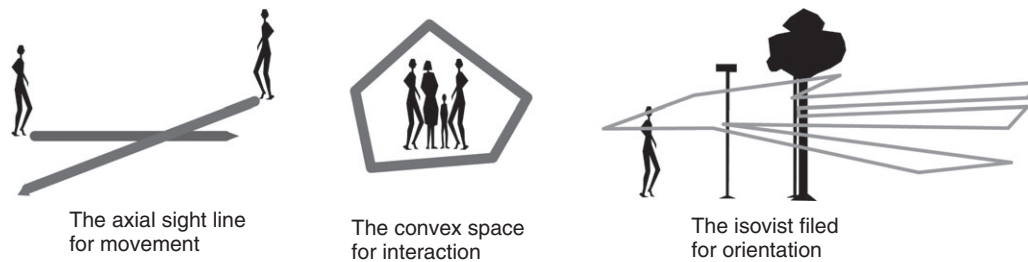


Figure 1 Three basic elements for analyzing visibility.

hidden behind a building, which affects his or her isovist field.

Point depth analyses show the degree of visibility from every point to all others in the public spaces of a neighborhood. This method is useful to test out where the most visible and less visible areas are in urban squares with freestanding objects. In practice, all public spaces in a built environment are rasterized by a grid. Each point for the visibility analyses is taken from the center of each cell's square. How integrated each point is in relation to all other points is calculated. Obstacles like walls, fences, and trees contribute to increasing the visual relationships between various cells.

An *axial line* represents the longest *visual sightline* in an urban space, and also represents the way human beings move in lines through the urban street network. It is the basis for analyzing degree of spatial integration. Direction change analyses measure the *to-movement* potential, while angular deviation analyses with metrical radiuses measure the *through-movement* potential. Each of these two types of relational pattern can be weighted by three different definitions of distance. The *metric* distance measures a town's street and road network as a system of shortest paths, while the *topological* distance calculates a town's street and road network as a system of fewest-turn paths. Finally, the *geometrical* distance calculates a town's street and road network as a system of least angle change paths. Each type of relation can be calculated at different radii from each street segment, defining radius again in terms of either shortest, fewest turns or least angle paths (Hillier and Iida 2005, 557–558). Together these spatial measurements can show the degree of spatial inequalities on various scale levels, and the results are useful

in gaining understandings of socioeconomic activities based on the information encoded in the physical form of excavated towns or past built environments.

Figure 2 shows a point depth and all-line analysis. The large open space in the square is the most integrated one (colored in black), while spaces behind buildings and trees are the most segregated ones (colored in light gray). An axial analysis carried out on Pompeii's street network revealed that shops were located along the highest integrated streets.

The degree of visibility between buildings and streets can also be measured. Degree of intervisibility between entrances influences the degree of social control. In practice, the number of inter-visible doors and windows is divided by the total number of houses in each street segment. The percentages can be grouped in 100, 75, 50, 25, and 0 percent intervisibility for each registration. Thus, two buildings with two entrances facing towards each other indicate 100 percent intervisibility of doors. Conversely, a street segment with a high density of entrances on only one side of the street segment is defined as 0 percent intervisible. These values can then be interpreted in order to shed light upon socioeconomic life. For example, a high density of entrances directly facing a street segment on only one side can be an indicator of an active street life, yet one lacking in social control (Van Nes and López 2010).

When applying space syntax to excavated sites it is important to clarify the chronological context of the analysis. Often, changes to the street network and buildings through time are layered upon each other, like, for example, Ostia (Stöger 2009). Some layers might be lost, while others are highly visible. While archaeologists aim to understand how the various spaces on an excavated site

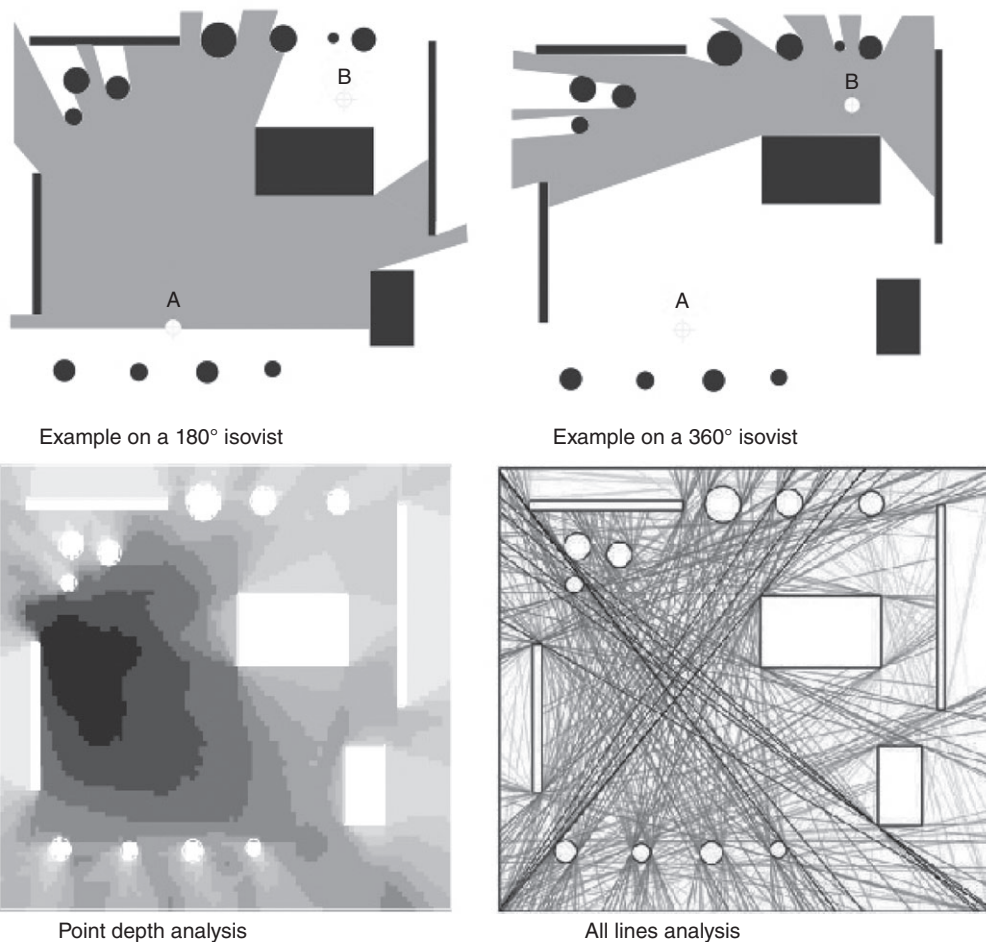


Figure 2 Examples of isovist fields, point depth, and all-lines analyses.

were used through the identification of excavated artifacts, visibility analyses enrich this by giving indications on the degree of street life, location of economic activities, and degree of social control between buildings and the spaces between them.

The results of the application of visibility analyses on excavated towns and buildings show many similarities with present built environments. When a street segment is on a spatially integrated main route, more buildings are directly connected to streets, and the entrances on each side of the street are intervisible to one another. Conversely, the further away a street segment is from a main route, the more building entrances are hidden away from streets and the degree of intervisibility between them is lower. The further

away from main routes, the more silent street life tends to be.

Take, for example, studies of Pompeii. Here shops and bakeries are seen to locate in the most integrated streets, with a high number of connections to other streets in a short metrical distance. Likewise, these streets have a high density of intervisible entrances connected to them. Religious buildings and political institutions locate themselves one direction change away from the most integrated streets. They are seldom located along or at the end of the integrated main streets. Brothels locate in side streets metrically close to the integrated main streets. In contrast, workshops, taverns, and drinking places are located along the main streets and in side streets close to

main streets. Conversely, the public baths, theatres, inns or hotels, sport, and leisure facilities are spread throughout the town's street network. The challenges for applying visibility analyses on excavated sites are as follows: in the first instance, a reconstruction of a town's street pattern must be available. Second, precise mapping of walls and entrances provides the basis for measuring a street's degree of intervisibility. In cases where it is impossible to ascertain a site's street network, visibility analysis between buildings and streets can to some extent give spatial indications as to how lively or quiet a street probably was in the past. To some extent, various visibility analyses can also indicate functions in adjacent buildings where identifiable artifacts are lacking.

SEE ALSO: Visibility Modeling

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Laser Scanning

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Laser scanning provides archaeology with a high-speed process for the acquisition of three-dimensional (3D) spatial data. The technique provides surface-based 3D measurements of any small- or large-scale, complex, irregular, standard or nonstandard real-world scene. The resulting data are visualized through the production of point clouds, with the final results depicted as line drawings, computer-aided design (CAD) models, 3D surface models, and video animations (Boehler and Marbs 2004, 292), acting as an enhanced communication tool that has the ability of visualizing real-world objects in 3D space. It is the most effective way to quickly obtain data from the observed object and it enables measurements of areas that were unable to be collected previously, such as through hand-based drawings or total station surveys (see TOTAL STATION).

Laser scanning data are collected through a systematic regular grid pattern, whereas recording methods such as photogrammetry (see DIGITAL PHOTOGRAMMETRY) concentrate on an object's discontinuities and representative structures (Grussenmeyer et al. 2008, 215). Through the collection of multiple scan positions, overlapping datasets are produced, and through a systematic recording methodology, an overall model is produced.

Three different types of laser scanning technique exist: triangulation or range laser scanning; time-of-flight laser scanning; and phase laser scanning. Each method captures and processes the recorded objects in different ways. These three techniques follow the same methodological approach of pre-processing the data via scanner operation and examining the object or site in question; recording the objects; stitching the multiple scans together; and processing the results. Although similar methodologies are used, differences can be seen in each.

Triangulation or range laser scanning is a technique that is more suited to the recording of small objects (less than 1 m). The technique works by projecting a light spot or line onto the surface of an object. The position of the spot or line is recorded through a charge-coupled device (CCD) camera, while the angle of the light beam is recorded by the internal mechanisms of the scanner; a calculation is made between these two elements and the relative distances are determined. The accuracy of the final scan data is reliant on the accuracy of the light angle recorded (Boehler, Heinz, and Marbs 2002, 434). Errors occur within any type of laser scanning method and they become prominent in the triangulation dataset when recording edges. The errors seen within edge detection are a flat triangulation of data that are unrepresentative of the original, and occur when part of the laser point or line is partially visible on a surface edge.

Triangulation-based scanners require a number of multiple scan positions that are close to one another to avoid general issues within the field of view. The process involved includes a range map capture; conversion to point data; meshing; and removal of unwanted errors. Multiple scans provide a jigsaw effect where each of the scans is unified as one; the majority of data that are collected are redundant due to overlap. Most triangulation-based scanners work within a limited range of light and will not work if the ambient light is too dark or too bright. They will also not record black or shiny surfaces unless blue light technology is incorporated within the scanner system. Blue light technology projects a pattern across a surface where two cameras capture the displacement of changing pattern; this depth variation in the displacement of the pattern provides a calculation of the measurements. Unlike the CCD camera system, where single measurements are taken based on where the light contacts the part of the surface recorded, the blue light allows for a complete surface capture. Blue light technology follows more of a structured light processing variation but enables

micron resolution and has the ability to record dark and shiny surfaces.

Time-of-flight scanning is a technique that is based on the understanding of the speed of light. The method works by projecting a laser beam onto a surface that is returned along the same path. As the speed of light is known, the scanner calculates the time that it takes for the laser to return, creating a distance based on time. A time-of-flight scanner is usually set up to record these lengths at intervals of a picosecond through a rotating mirror, allowing several hundred thousand points to be captured in a second. The method can be used on a wide range of areas and is more suited to recording landscapes, through a 360-degree horizontal view from the ground, and in a fixed position for light detection and ranging (LiDAR) capture (see AIRBORNE LASER SCANNING AND LIDAR). The majority of scanners have the ability to record a distance of up to 300 m, with some Leica scanners having the ability to record up to 600 m. Most time-of-flight scanners allow for the resolution and the distance of the point data to be set manually within the capturing software. Photographs are also captured during this process and are projected onto the point clouds to provide red, green, and blue (RGB) values per point.

Time-of-flight laser scanners can be seen as an advanced total station (see TOTAL STATION). One main drawback to the technique is the time associated with recording one scan; this is dependent on the distance and resolution chosen, as well as the equipment used, but can take several hours to complete. Smaller distances do not equate to shorter scan times as a greater point density can be recorded. When collecting data, a consideration has to be made in terms of the level of detail required and the time available to record these scans. The majority of operators will place the scanner in a central position, record an overall scan, and then focus on specific areas at differing point spaces. Further considerations have to be made in terms of the areas recorded, especially in large public spaces. To capture longer distances, a stronger light source is required; most time-of-flight scanners utilize a class 2 or 3 laser, requiring the operator and public to be set distances away for health and safety reasons. Creating scans in public spaces also becomes problematic when the laser is interrupted by

movement, creating unwanted data and potential errors in the returning signal.

Phase laser scanning is similar to time-of-flight except that comparisons are made between outgoing and returning signals of a single laser beam rather than through the time taken for the light to return to the device. Phase laser scanning does this by modulating the power of the laser beam, where changes in distances are calculated through the differing returned frequencies (Petrie and Toth 2008, 18–19). The technique provides a greater accuracy of data due to the phase shift of the laser beam; it provides a faster data acquisition and offers a reduced amount of erroneous data. The technique works best within a limited distance range of up to 100 m. The method, as is the case with time-of-flight, allows for the collection of data in all ambient light conditions, from very dark to extremely bright environments, and includes the capture of photographs. The majority of existing phase scanners work with a limited manual control concerning distances, point spacing, and color exposure. Unlike the time-of-flight technique, the scanners cannot specify exact areas of interest and focus on a specified field of view. The systems provided by Faro are lighter and easier to work with and include a global positioning system (GPS) device, height sensor, compass, and high-dynamic range (HDR) imaging technology (see COMPUTATIONAL PHOTOGRAPHY). The phase systems currently available incorporate a class 1 laser, limiting the range of the device but making it safe for all capture scenarios. For both the time-of-flight and phase systems, targets can be used in the collection of the data to assist the stitching process. Current software packages allow for a direct cloud-to-cloud comparison, providing great control over the stitching process.

There are many issues that need to be considered when using laser scanning within archaeology: namely registration of the scans, field of view, density of data capture, and the ability to add additional information (Barber, Mills, and Bryan 2003, 620). A scanner relies on what it can see; if obstructions are present, no usable data will be collected. If the data are captured with too high a point spacing, the model will show little surface differences; if the point spacing is too small, the data may be too data intensive to use. The higher the point density, the greater the computing power needed and the greater the

file size. Within archaeological-based recordings, environmental issues are also a concern. Inadequate mounting of the device can lead to the field of view being limited and key regions missed. Nearby vibrations lead to errors in the recorded data; and temperature variations in the scanner (going from cool to hot areas) affect the operating functionality and ability. Within the recording process, errors can also be created through the capture of reflective, opaque, or uneven surfaces, where the returning laser signal is sent back via different angles or not at all. Developers have many ways of counteracting these complications, through range limits, laser class type, increased field of view, and better registration software to remove erroneous data.

There are disadvantages associated with the use of laser scanning. The first is that laser scanning, through the collection and processing of the data, takes a significant amount of time, skill, and money to complete. The time associated with producing a finished model varies, but for every day spent capturing, a week of processing is required. This can be reduced depending on the object or site that is recorded and through the correct preparation and forward thinking of how each scan will be registered. The technique is not suited to recording every type of material or surface: shiny reflective surfaces may reflect the laser; black areas absorb the laser and affect the return rate; and transparent features, such as glass, will struggle to record only the exterior surface detail.

The method is not the best tool for recording all archaeological features and should not be used instead of traditional means (see FIELD SURVEY); rather, it should be used in conjunction with them. It provides a complete replica of a given site or object and allows for a number of post-processing options to help with understanding the past. The method is time consuming, but the results provided are generally superior to other types of surface recording methods. Methods such as photogrammetry (see DIGITAL PHOTOGRAMMETRY) are comparable, but the results gained are reliant on the operator and camera system used; structured light scanning provides equally suitable data to triangulation-based scanners but relies on manually calibrated light patterns; computed tomography (see COMPUTED TOMOGRAPHY) provides internal and external details but is too

expensive for most archaeological research. The use of laser scanning within archaeology is on the rise, but its use should be dependent on the research questions asked and it should not be used simply because it is an available tool. Great skill, time, and resources are necessary to produce usable data. Without training, the production of models can be greatly hindered and errors contained within the data can affect the outcomes of the research.

SEE ALSO: Structure from Motion

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Lidar Data Visualization and Processing

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Light detection and ranging (LiDAR) data processing for archaeological purposes converts raw point clouds into products that support archaeological investigation and can be more readily manipulated. The practice comprises the following tasks: automated classification of returns; manual editing and enhancement; accuracy assessment and quality control; generation of products; and visualization for feature detection and interpretation. The tasks are iterative and often overlap.

Automated classification of returns

One of the key benefits of using Aerial Laser Scanning (ALS) for archaeological exploration is the ability to strip away vegetation cover where gaps in foliage allow laser scanning to penetrate to the ground surface (see AIRBORNE LASER SCANNING AND LIDAR). A certain percentage of detected returns, depending mostly on vegetation density, will come from the ground even in woodland, thus allowing the creation of a bare-earth elevation model and observation of archaeological features in forested and scrub landscapes. To accomplish this, returns must be classified in the first stage of LiDAR data post-processing (processing steps applied to LiDAR point clouds). Classification (also referred to as filtering) assigns descriptive classes to LiDAR returns in accordance with a classification scheme (typically

bare-earth terrain points (ground), noise, vegetation, buildings, but also other anthropogenic features and objects of interest, and water). The primary task is to distinguish ground and non-ground points and this process is usually highly automated.

An essential step that can be done either before or during automatic detection of ground points is the identification and indication of noise—that is, extremely high or low points outside the range of likely elevations for the project area. The main benefit of flagging (tagging, attributing) noise points at the beginning is to gain better control over the visual representation of a point cloud, because software packages rely on statistical minimum and maximum values to color code it. Most classification algorithms are very sensitive to the influence of low noise and therefore have built-in procedures for its exclusion. However, manual identification of low noise is often required for specific applications that demand very exact representation of terrain, for example hydrology and archaeology.

Among the more important parameters that define the classification process are relief severity (flat, rolling, hilly, mountainous), vegetation cover (open, light, medium, dense vegetation), level of urbanization (individual houses, blocks, skyscrapers, warehouses), and point density. Different ground-filtering algorithms have been developed to cope with specific tasks or environments. Pfeifer and Mandlbauer (2008) describe, evaluate, and compare the currently available algorithms, and combine them in four groups:

- morphological filters, which are based on the principal presumption that the smaller the distances between a ground point and its neighboring points, the lesser the height difference accepted between them;
- progressive densification filters, which rebuild the ground by iteratively classifying more and more points as ground;
- surface-based filters, which start by initially assuming that all points belong to the ground surface and then remove those points that do not fit;

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- segmentation-based filters, which initially group points into homogeneous segments and then classify segments rather than individual points.

There are many variants and extensions within each group and some classification algorithms combine different approaches. Software developers do not usually disclose the details of the solution implemented, but may provide some basic guidelines for choosing parameters in different environments. Thus, users mostly gain knowledge and experience through trial and error. This can be frustrating because using the most appropriate algorithm with optimal settings is fundamental to producing the best possible elevation model in which archaeological topography will be represented. Archaeologists therefore have to be aware of the types of classification errors likely to be introduced by different filtering algorithms, as these may make the difference between features of interest being included in derived models or being excluded.

Aggressive settings of filtering parameters remove points that should be retained, for example, classifying small ridges or peaks as vegetation, producing type 1 errors, which are more common with data that have been processed for purposes other than archaeology. These errors can have a detrimental impact on detection of archaeological remains because small-scale topography may be classified as vegetation and will therefore not be present in the elevation model or in any of the subsequent visualizations. On the other hand, inclusion of points that should be removed, for example, retaining some vegetation or buildings points, produces type 2 errors. This results in some visible artifacts in an elevation model. With good knowledge about the behavior of the algorithm used, artifacts are quite predictable and restricted, and do not pose a big issue for interpretation.

When producing an elevation model for archaeological interpretation, the practical aim is usually to optimize the settings of filtering algorithms in such a way that vegetation is removed while the morphological characteristics of small relief features underneath it are preserved to the maximum extent. This can mean that buildings and other similar “discontinuities,” which need relatively aggressive filtering, will remain in the

resulting digital elevation model (DEM), which is not therefore strictly bare-earth terrain (see further discussion later).

Manual editing and enhancement

Because automatic classification is only accurate to a certain extent, visual inspection and manual classification are essential steps in obtaining a good result. This involves familiarity with the specific landscape, and knowledge of fundamental mapping principles, conventions, and best practice. Manual classification therefore relies heavily on the experience of the operator. Refinement of the elevation model is usually done on a point cloud which has been previously classified by an automated algorithm, reassigning points that have been categorized incorrectly. Points can be colored by intensity, classification, height (relative or absolute), or drape (single or multiple rasters), and viewed against background imagery (orthophotos, produced elevation models, thematic or topographic maps), as profile cross-sections, or in three dimensions to check for anomalies and artifacts.

Decisions on which area to inspect more carefully and which points to reclassify depend on the overall geomorphology and type and structure of the vegetation typical to the area. Special attention has to be paid to rough terrain or discontinuous slopes, dense forest areas with very few ground returns, and regions with low and dense vegetation that is often ignored by ground filters. The occurrence of different artifacts or unnaturally smooth terrain can be effectively predicted by mapping the density of laser points representing the ground and density of the vegetation canopy above them. Automated filtering will often remove valid ground points where steep berms and levees have been constructed in flat terrain, as it is unable to distinguish them from a row of vegetation. For the same reason, most filters remove narrow upstanding structures, such as walls, under a canopy and the operator might wish to reclassify these. While carrying out manual classification on a large dataset may be beyond the resources (or interests) of many archaeological projects, careful checking and correction of the classifications over areas of interest

can help in the recognition of archaeological features and is fundamental to the creation of good elevation models for visualization.

Accuracy assessment and quality control

Quality control is a compulsory step for ensuring that the acquired dataset meets the accuracy requirements and is fit for purpose of intended inquiries. Data providers have to implement routines and consistent checks to ensure data integrity, correctness, and completeness. Various public agencies and private entities have published a number of guidelines and standards for accuracy and quality reporting for LiDAR data products, which list many parameters that have to be recorded and assessed, both quantitatively and qualitatively. The most important ones that digest the data quality and that every user should be familiar with are the planimetric and vertical accuracy of acquired points, pulse density, (ground) point density, the quality of classification, possible data gaps, and lack of overlap. For archaeology, the average density of (all) points is of minor importance to the knowledge of the distribution and density of ground points and data gaps. Also important is the visual inspection for artifacts and anomalies, which not only are aesthetic but also affect the accuracy of analyses based on the terrain surface.

Generation of products

Rather than looking at the point cloud, interpreters spend most time inspecting rasterized products such as elevation models and, even more frequently, derived visualizations. The method used to produce the elevation model from the point cloud is important, because one wants good models even in places where the density of ground points is insufficient to accurately map the ground under forest at a given resolution, despite a high scanning density. In such cases, the rasterization algorithm has to “fabricate” (infer from neighboring points) the representation of the ground. The appearance of this fabricated ground varies, but the most important influence of various algorithms is on

the general smoothness and preservation (clarity) of edges. In general, the Natural Neighbors (NN) method generates a very smooth terrain, Inverse Distance Weighted (IDW) method introduces steps, rasterization with Triangulated Irregular Network (TIN) introduces triangles, and splines create a range of artifacts.

Typical rasterized products include various elevation models, such as a digital bare-earth (terrain) model (DTM) and a digital surface model (DSM), which includes vegetation and is thus useless in forested landscapes but can be superior to a DTM for detecting archaeology in meadows, and any other type of DEM—for example, containing terrain and buildings, point density calculations, and intensity of return image. Having buildings included in the elevation model is not a problem because buildings do not obstruct the view of small topography, and in many cases help improve interpretation as they offer visual clues to the age of cultural features of interest and are distinct orientation points in the landscape.

While any one of the rasterized products gives certain information about the landscape, to explore the archaeological topography thoroughly, DEMs have to be presented with specific visualization techniques.

Visualization for detection and interpretation

Some visualization techniques can only have a presentational value, while others based on specific spatial analysis (see SPATIAL ANALYSIS) can produce results that are related to physical quantities. While the latter have mainly been developed in other scientific fields and for specific purposes, they have also proven useful for making sense of detailed elevation models. Their archaeological value varies significantly with respect to the characteristics of structures observed, including size, shape, orientation, concavity or convexity, degree of prominence, and edge type. Not all methods can be recommended for interpretation when relative or absolute comparisons need to be judged. This is because most visualizations can change the observable properties of structures, depending on the settings used in the calculation. While there is no ideal visualization that would

be effective in all situations, a good visualization should meet the following criteria:

- Small-scale features must be clearly visible.
- The visualization must be intuitive and easy to interpret, that is, the users should have a clear understanding of what the visualization is showing them.
- The visualization must not depend on the orientation or shape of microrelief features.
- The visualization should work well in all terrain types.
- Calculation of the visualization should not create artificial artifacts; it can, however, highlight the existing ones.
- It must be possible to calculate the visualization from a raster elevation model (either a terrain model or as a result of dedicated processing).
- It must be possible to study the result at the entire range of values (saturation of extreme values must be minimal also in rugged terrain).
- Color or gray scale should be effective with a linear histogram stretch; manual saturation of minimum and maximum values is allowed.
- Calculation must be fast; that is, it should not slow down the interpretation process.

The assessment and evaluation of several visualization techniques has been carried out by Kokalj, Zakšek, and Oštir (2013). It is difficult to categorize them in exact groups because of their complexity, usefulness in a range of applications, various computational methods, and combinations. The following paragraphs therefore list a few of the most common methods used in archaeology, along with their main characteristics.

Analytical hill-shading is the most common technique of relief representation. It is based on direct illumination which makes it possible to intuitively recognize relief features. However, it also has several drawbacks. The most critical are its inability to represent linear objects that lie parallel to the direction of the light source and saturation of shadow areas. A number of authors have commented on its shortcomings and proposed routines to at least partially overcome these, for example with shading from multiple

directions and summarizing the results with principal component analysis (see PRINCIPAL COMPONENT ANALYSIS) (PCA). PCA removes redundancy, so there is no need to look at multiple images, but it is data dependent so does not provide consistent results with different datasets.

Methods of relief illumination include solar radiation modeling, sky illumination modeling, sky-view factor, anisotropic sky-view factor, and openness. The first two are very demanding to compute. Solar radiation models also suffer from saturation in shadows, but give information about the suitability of landscape for settlement and agriculture. The others are proxies for diffuse illumination and are very good for revealing micro-relief morphology. They do not produce saturated areas and provide clear distinction between protruding features and depressions, so they are particularly useful for observation of complex features on varied terrain. Openness is also a trend removal method and completely removes the sense of general topography. Sky-view factor, on the other hand, preserves the sense of general topography. It is a good all-purpose technique, and works especially well in combination with other methods, for instance hill-shading and slope.

The techniques of local range adjustment of height values (histogram stretch, color cast, color ranging, elevation differentiation) are best for very flat areas because linear histogram stretch retains the visual information on elevation; however, they do not work with uneven terrain. With terrain, especially if slopes are gentle and long, trend removal methods can be used to produce local relief models. The basic idea is to calculate the broader morphological features, such as hills and valleys, and remove them from the terrain data so only the small-scale features remain. Local relief models highlight small topographic differences and can be used as input to other methods. The main disadvantage is that they introduce artifacts, such as artificial banks and ditches, that can mislead the interpreter. Slope gradient presented in an inverted grayscale retains a very plastic representation of morphology and when shown together with hill-shading works well on most types of terrain. Two noteworthy techniques are also local dominance and multiscale integral invariants, which are especially suitable for detection of very subtle features.

Spatial (convolution) filters, for example those developed by Laplace, Robert, Sobel, Prewitt, and Frei and Chen, enhance high-frequency information. The main problem with using these is that along with emphasizing the features of interest they also accentuate noise in the data, but are nevertheless useful when searching for very distinct structures. Many other terrain visualization techniques exist and occasionally they are evaluated for specific use in archaeology. The described techniques not only are suitable to present LiDAR relief models, but also can be used with raster elevation models produced from any other source, for example image-based 3D modeling or structured light scanning. They can be applied to data of different spatial resolution (local, regional, continental, global), representing various entities (object, site, landscape).

Automated archaeological feature extraction

Research is now focused on automated processes that support detection and interpretation of anthropogenic relief. The whole procedure from point cloud classification to generation of various visualizations can already be highly automated; however, the processes of observation, interpretation, feature identification, and creation of archaeological information (i.e., an interpreted map) are still mostly operating in human time—that is to say, they can only proceed at the rate at which an individual can examine images, identify features, and map them (Cowley 2012). With larger (countrywide), more complex, and accurate LiDAR datasets becoming freely and openly available, the pressure is now on to develop techniques that will enable automatic detection, if not interpretation, of archaeological features. Cowley (2012) argues that visual inspection and (semi) automatic approaches should be complementary and both used in appropriate contexts, recognizing, for example, the different demands of extensive mapping where site detection is paramount or detailed understanding of a landscape where archaeological experience and knowledge are important. Continual and iterative improvement of processing algorithms has already enabled successful detection of pits and mounds, especially in a

“controlled environment,” that is, a setting with few similar modern or natural features, while automatic detection of other archaeological features of regular geometric shape, such as squares and straight lines, remains elusive precisely because of the difficulties of weeding out modern anthropogenic content. Most methods involve a form of template matching or geographic object-based analysis, and decision rules. For now, the results of automatic archaeological feature extraction therefore provide insight into a general spatial pattern rather than accounting for all individual features.

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SEE ALSO: Laser Scanning

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Magnetic Resonance Imaging (MRI)

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Magnetic resonance (MR) scanning is most often understood as image acquisition of anatomic structures in patients, and this nondestructive scanning technology is a widespread clinical diagnostic modality. Magnetic resonance imaging (MRI) provides not only static anatomical images, but also dynamic recordings of functions in various organs such as the heart, the kidney, and the brain.

Magnetic resonance is based on the precessing movement of nuclei aligning to the static magnetic field of an MR scanner. The precessing frequency (Lamour frequency) is determined by the strength of the static magnet field and a so-called gyromagnetic ratio specific for the individual nuclei. The precessing frequency for ^1H in a standard 1.5 Tesla magnet system is around 63 MHz, which is very close to the commercial radio transmission frequency. Electromagnetic waves used for excitation of atoms at this frequency do not imply any ionization in tissue. Some precessing atoms align to the direction of a permanent magnet field and can be excited by the radio waves transmitted through an antenna system (coil). Through this excitation, atoms absorb energy and flip into an orientation anti-parallel to the direction of the static magnetic field now carrying a higher level of energy. When the excitation is ended, the anti-parallel-oriented nuclei will start a flip-back process and the release of absorbed energy. This can be recorded by a receiver coil system.

High pixel resolution, optimal signal-to-noise level, and recording time are always compromises in clinical scannings. However, scanning time is usually not an issue when scanning archaeological artifacts. As a result, scan data can be acquired with a pixel resolution in 3D scans well below 1 mm, and at the same time with

sufficient signal-to-noise ratios. Even though mobile scanners loaded on a heavy truck exist, most scanners are stationary installations difficult to bring to remote locations (Rühli et al. 2007). Scanner designs for many different purposes are on the market. Closed magnets come in sizes ranging from a few millimeters to more than 60 centimeters in bore diameter. Open scanners exist as well, for instance for veterinary use, and desktop magnets. A broad range of field strengths are used; but, in small-bore magnets with higher fields, image resolutions can be much better than in whole-body clinical scanners. If archaeological remains can be removed and prevented from drying out, tissue structures can be visualized as in Figure 1, which shows an MRI of part of the intestines of a more than 2,000-year-old Danish bog man (Stødkilde-Jørgensen et al. 2007). The intestinal tissue was preserved in alcohol shortly after its discovery and MR-scanned more than fifty years later. Even though only the submucosal layer of the intestinal wall is left, the image contrast is still sufficient.

The major strength of MRI is the possibility to encode the individual pixel values in the images (image weighting) with a large range of biochemical or physiological properties coupled to the concentration or movement of specific atoms. Due to the large availability of and strong echo from the hydrogen nucleus, this is most often the basis for MRI. Water and fat in the body add substantially to the total proton concentration, and thus to the MRI signal intensity. Spatial information on atom movements can be used for depicting water diffusion in the tissue, and in this way it is possible to estimate a so-called apparent diffusion coefficient dependent on the water content distribution between the interstitial space and the intracellular space. Further to this, diffusion tensor images of longitudinal tissue structures can be depicted, for instance axonal fibers in the brain or muscle fibers.

MRI in archaeological artifacts such as ancient mummies is often hampered by the usually very low amount of water present in the specimen, as the hydrogen atoms in water are the origin of the signals used for MRI. To avoid bacterial or fungal

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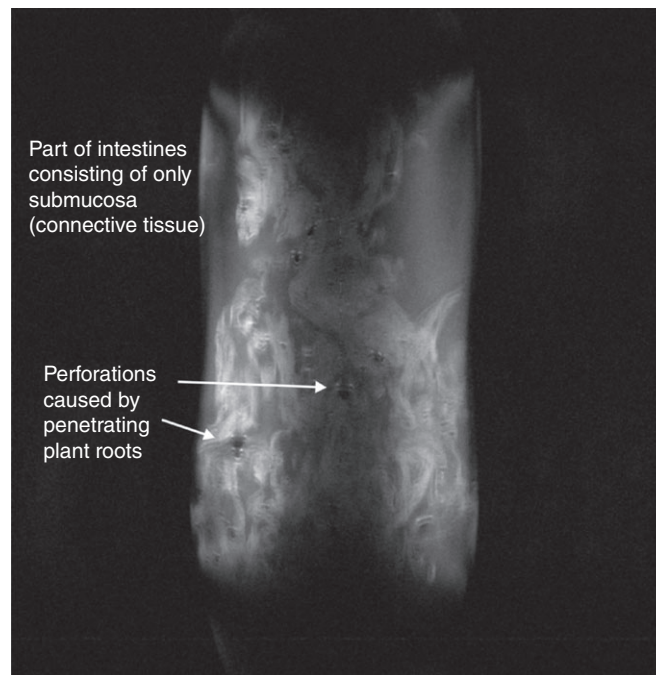


Figure 1 Part of the intestines of a more than 2,000-year-old Danish bog man visualized with MRI. Source: Stødkilde-Jørgensen et al. (2007).

growth, most museums keep the mummified artifacts dried out; what is more, they may have employed different conservation maneuvers, with wax or tanning. These present difficulties for applying MRI scanning that can be overcome to some extent by using MR sequences with very short echo times. These MR excitation sequences have been developed along with the ongoing technical improvement of equipment performance and compensate for the low content of moveable hydrogen atoms in dried-out soft tissue and for short transverse relaxation times in solid tissue such as bone structures. With such ultrashort echo-time excitation sequences it has been possible to visualize anatomical details in an ancient mummified hand dehydrated with natron and embalmed with resin (Ozen 2016).

In ancient Egypt artificial mummification was carried out by applying a blend of NaCl , Na_2CO_3 , NaHCO_3 , and NaP_2SO_4 (natron) directly onto the body surface. The subsequent high concentration, especially of sodium, in the artificial mummification suggests that MRI based on the ^{23}Na atom could be applied together with ^1H MRI, as done by Münnemann and colleagues

(2007). The latter measurements showed a proton signal only from structures close to the skin surface. However, the ^{23}Na MRI demonstrated enhanced sodium signals in the entire body after the natron-based mummification process.

In some cases, specific burial traditions—for example the use of encapsulated lime–soil mixtures—ensured a relatively hydrated condition (Shin et al. 2010). In mummies buried in this way in the seventeenth century, the burial method resulted in well-preserved organs that contained enough water to enable the visualization of detailed organ structures through MRI.

MRI uses so-called Fourier transformations of the signals echoed back to the receiver coil after a radio frequency excitation. These transform the analog time-domain echo signals into the frequency domain by a number of temporal and spatial preserving operations in the image reconstruction process, leading forward to the final image. In contrast to MRI, however, in the other major MR technique, called magnetic resonance spectroscopy (MRS), the processing complexity is limited. Basically, MRS is a relative concentration measure of various molecules in

the tissue. Which molecules are visible depends on the tissue type and on the atom type excited by the radio frequency excitation. In archaeology, MRS can be applied both to organic materials and to inorganic dry materials by using so-called solid-state nuclear magnetic resonance (NMR) spectroscopy. For example, in living brain tissue, ^1H spectroscopy will show the relative concentration of N-acetylaspartate, choline, creatine, and *myo*-inositol. ^{13}C in devitalized tissue will show a number of peaks related to various fat chains. In general, because of the capacity to quantify specific chemical molecules, spectroscopy allows for studies of nutritional status, authenticity, and sources in archaeological artifacts (Giovannetti et al. 2016).

The inorganic phosphate concentration in wet archaeological artifacts might be quite low, depending on the type of the preserved tissue, for example connective tissue from corpses found in wet moors. Furthermore, if the volume of available tissue is low, solid-state NMR spectroscopy is required, which differs from clinical MRS by allowing samples as small as one cubic millimeter of wet or dried tissue (or smaller) to be analyzed. Solid state also uses a number of techniques such as multinuclear cross-polarization (CP) and magic-angle spinning (MAS) to improve the signal-to-noise ratio.

In a study of tissue samples from the intestines of a 2,000-year-old Danish bog man (Stødkilde-Jørgensen et al. 2008), solid-state (CP) ^{31}P and ^{13}C magic-angle spinning multinuclear cross-polarization NMR were used and the resulting measurements were compared to those from a recent, surgically removed intestinal specimen.

The ^{31}P MAS spectra of the intestine from the bog man exhibited extremely low sensitivity when acquired without CP (i.e., through single-pulse excitation), and overnight runs acquired with 40,000 transients were necessary to achieve an acceptable signal-to-noise ratio, demonstrating a very broad spinning sideband (SSB) pattern.

The ^{31}P CP/MAS spectrum found in tissue from the recently deceased person was acquired at 9.4 T (161.9 MHz) using spinning speeds of 4 kHz (a) and 6 kHz (c) and a 5 mm rotor. Both spectra required acquisition of about 5,000 transients (~6 hours). In contrast to the ^{31}P MAS spectra from the bog man specimen, only a few hours of consecutive data sampling from

the deceased person were enough to generate an excellent signal-to-noise ratio. ^{31}P CP/MAS showed more than a twofold increase in intensity by comparison to the single-pulse ^{31}P MAS spectra without CP; furthermore, the line width of the individual SSBs was quite small by comparison to those in the ^{31}P MAS spectrum of the bog man. Computer simulations of the experimental ^{31}P CP/MAS spectra acquired with the two different spinning frequencies demonstrated that these spectra could be characterized by a single set of ^{31}P chemical shift isotropic and anisotropic (CSA) parameters ($\delta_{\text{iso}} = -0.64$ ppm, $\delta_{\sigma} = 97$ ppm, and $\eta_{\sigma} = 0.65 + 0.03$). A ^{31}P CSA of similar magnitude ($\delta_{\sigma} = 90$ ppm) and $\delta_{\text{iso}} \approx -3$ ppm also characterized the ^{31}P MAS spectrum of the spectroscopic data from the bog man.

The overall results of the MRS measurements showed that the ^{31}P constituents of the intestine of the bog man could be identified as single inorganic phosphate and showed a ^{31}P concentration that was lower by more than two orders of magnitude than the concentration in the intestine of a recently deceased person. This difference in inorganic phosphate content could very well be explained by the wet conditions under which the bog man was preserved for more than two millennia, which resulted in the chemical release of inorganic phosphate and its later removal through the aqueous environment in which the body was submerged.

SEE ALSO: Chemistry in Archaeology;
Magnetostatigraphy

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Multi-View Stereo

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History

The idea to use image pairs with sufficient angular separation to create the perception of depth dates back at least to the invention of stereoscopes in Victorian times. In the field of topographic surveying and map production, stereo image pairs served as the primary source of data for the extraction of elevation models from aerial photographs (using first manual and later digital methods) until the introduction of light detection and ranging (LiDAR) (see AIRBORNE LASER SCANNING AND LIDAR) technology. These traditional “two-view” (stereo) approaches find their natural extension in early limited “multi-view” methods, initially aiming at improving the robustness of stereo image processing. By the turn of the millennium, the fundamental mathematics for reconstructing three-dimensional (3D) geometries from an arbitrary number of views (*multiple* or *n-view* geometries) had been firmly established in computer vision. Recent advances in software technology, which have allowed *multi-view stereo* (MVS) technology to enter broad and general fields of application, have been driven by the general availability of high-resolution digital cameras and unprecedented computing power in consumer personal computers. However, the extension of MVS to large digital image series has also shifted the focus of interest to increasingly ambitious and computationally demanding tasks, such as reconstructing full 360-degree models of photographed objects or scenes. The ensuing challenges, of a technical and mathematical nature, are beyond the scope of the two-view approaches found in stereo photogrammetry (see DIGITAL PHOTOGRAMMETRY) and MVS has since evolved into its own subject of research and development.

Archaeology and architecture are favorable applications for the development and comparison of 3D reconstruction methods, as the often intricate motives found there pose interesting structural challenges for geometric reconstruction, and at the same time provide attractive and highly recognizable case studies. Practitioners in the domains of archaeology and heritage have been among the first to benefit from advances in MVS (recent examples include Dellepiane et al. 2013 and De Reu et al. 2013).

Technology

The term “MVS” does not denote a single, well-defined mathematical method or algorithm, but rather a family of computational solutions for the problem of extracting dense point clouds from large image series. A range of MVS implementations in end-user software exist that share the technical property of pushing even the most current computing hardware to its limits. They also share a set of goals with regard to their usefulness. Ideally, any implementation of MVS should have the following desirable properties: (1) It should produce point clouds that are as dense, homogeneous, and complete as the images allow; (2) it should be robust, so that images with varying contents, resolutions, and contrasts can be processed in one unified model; (3) it should be fast and allow the processing of large image series in reasonable time; and (4) it should provide the best possible geometric accuracy that the input images’ resolution and quality allow.

One of the earliest successful approaches to MVS is to first extract the 3D structure of multiple stereo image pairs and then fuse the individual results into a single model in a second step of point cloud construction. The first step poses a relatively well-defined problem (also known as *optical flow* in computer vision) that can be solved by computing a so-called *depth* or *range map*. This usually results in a very dense and homogeneous grid of 3D estimates for the field of vision represented by each stereo pair. The second step,

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however, is computationally demanding and can make the processing of large image series impractical on consumer-grade hardware. Fusing depth maps into one point cloud is a nontrivial process, due to the requirement of filtering out much erroneous data (noise) that result from the heterogeneous quality of 3D estimates within each depth map (see Furukawa and Hernández 2013, 63). To alleviate this problem, the resolution of the input images can be reduced and the processing off-loaded to an external high-performance computing service, as exemplified by the “Arc3D Web Service” (Nilsson et al. 2007).

Since upload bandwidth can be as severe a bottleneck as locally available processing power, performance remains a key issue for the usefulness of MVS software. Consequently, more current and efficient approaches to MVS focus on computationally efficient *photo-consistency* functions. These are designed to quickly identify image regions that are visible from multiple viewpoints and extract 3D information from them, thereby avoiding the redundant computations involved in fusing multiple two-view point clouds (see Furukawa and Hernández 2013, 17–37). In addition, the high-performance streaming processors found in current consumer-grade graphics cards are increasingly used for computing essential mathematical functions in parallel, partly eliminating the need for expensive multiprocessor hardware. This is made possible by open standards such as OpenCL (<https://www.khronos.org/opencl/>) and proprietary interfaces such as CUDA (<http://www.nvidia.com>).

The most significant technical limitations to the potential of MVS are imposed by the properties of the input imagery (Furukawa and Hernández 2013, 127–130; see also notes on practical application, below). Since any multiview approach has to start by analyzing single images for distinct structural features (edge detection, color gradients, etc.), photos showing weakly structured, homogeneous areas (such as stretches of sand) often produce incomplete or geometrically impoverished 3D models, as do very thin structures (e.g., grassy patches) and reflective regions (e.g., water surfaces). Some MVS implementations, such as CMPMVS (Jancosek and Pajdla 2011) are at least capable of compensating visually for this by fitting simple textured surfaces into the problematic areas of the model,

although this approach has little effect on the lack of geometric detail.

The overall maturity and robustness achieved by current MVS technology means that many implementations leave their academic incubation stages and are transferred into proprietary software for sale, where they essentially act as black boxes in the data-processing chain. Few details are published about these implementations, but comparative studies and benchmarks that highlight their individual strengths and weaknesses are still possible (Remondino et al. 2012).

Application

Any MVS-based 3D model can only be as good as the images on which it is based. The minimum requirement for successful MVS is a set of matched images (see also SfM (see *STRUCTURE FROM MOTION*)) with sufficient overlap. Getting good results is at least as much a matter of adjusting photographic habits on the human side, as it is one of mathematical finesse on the software side. There are certain prerequisites which, if met, tend to produce good results more predictably. The key factors are sufficient *overlap* between successive shots and *complete coverage* from all angles. Images should be taken while *moving around* the object or scene. This is a significant departure from traditional photo documentation techniques where a carefully chosen, small number of views are captured from an equally small number of fixed camera positions.

Practical experience indicates that there are few (if any) limitations regarding camera and lens technology that cannot be overcome with a well-planned photographic strategy and some degree of image preprocessing. Parameters such as image resolution and lens quality are of secondary concern to MVS, as long as the image series is large enough. Cheap compact cameras with relatively low resolution and low-quality lenses can still produce images that are *sufficient* for many purposes, while keeping processing times low. In fact, given limited computing resources, the ability to process larger image series at lower resolution may outweigh the benefits of higher resolution imagery for applications such as large site and aerial surveys. In some scenarios, even extreme wide-angle lenses can be

useful, provided that adequate lens curvature correction is applied in a pre-processing step. Video streams produced by cameras with high frame rates (at least 60 frames per second, to avoid *rolling shutter* effects) can be a good alternative to single-shot imagery, as they provide extremely high overlap between successive frames.

Given MVS's low cost of operation, an important debate revolves around whether it can replace expensive scanning hardware, most notably close-range, terrestrial laser scanners (see LASER SCANNING) for general application. Whereas laser scanning is an active, tightly controlled acquisition process with well-known properties, assessing the smallest level of detail and its geometric accuracy (colloquially referred to as "precision") achievable by MVS is nontrivial. Distance to object, photo sensor resolution (true low-noise capacity, not nominal pixel count), and the suitability of the image series for dense reconstruction (see considerations above under "Application") are all involved in determining the smallest detail distinguishable in the generated point cloud. Regarding achievable geometric accuracy and level of detail, comparative studies of benchmark datasets indicate that the differences between image-based methods and close-range laser scans are insignificant for many practical purposes (El-Hakim et al. 2008).

Image-based 3D modeling has the clear advantage when it comes to sheer flexibility. Compact and light-weight camera solutions are readily available for operation in extreme environments, underwater, airborne, and even microscopic image acquisition. The same can be said about infrared and multispectral photo sensors (e.g., Casana et al. 2014), as well as recent technologies such as high dynamic range (see COMPUTATIONAL PHOTOGRAPHY) and light field photography. If photographs can be taken, then there is a good chance that 3D models of sufficient quality can be extracted from them. More importantly, if current software fails, then there is still a chance that advances in the rapidly maturing fields of image processing and computer vision will succeed where older software failed. Advances in MVS go hand in hand with those in SfM: Improved algorithms for feature extraction, image matching, and automated camera calibration continuously improve the results of MVS-based 3D reconstruction. Thus, one of the great potentials of

MVS lies in the possibility to extract detailed 3D models from existing collections of photographs, even those that were not acquired for that purpose.

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Multispectral and Hyperspectral Imaging

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What's in a name?

In the field of archaeology (and heritage in general), many documentation and examination methods are based on imaging techniques that characterize and depict artifacts in a nondestructive and mechanically noninvasive way. Multi- and hyperspectral imaging (together denoted spectral imaging) are two possible forms of such noninvasive imaging. Both are based on the detection of reflected or emitted optical electromagnetic radiation, the latter being defined as electromagnetic waves with wavelengths between 10 nm (0.01 μm) and 1 mm (1,000 μm). This detection can be better understood when considering that optical digital imaging usually generates a signal that is the outcome of a three-variable process:

- Electromagnetic radiation of a radiation source falls onto the object.
- This radiation is partly absorbed, transmitted, and reflected by the object. In addition to the specific chemical and physical structure of the object, this interaction and the specific ratio of the three processes is wavelength dependent. The interaction of both incoming energy and reflection creates a spectral radiance distribution that is sampled by the imager.
- The imager also has its own spectral response(s). It will detect and digitize the incoming radiance in specific spectral regions.

When observing a hot object, the imaging process is ideally governed by just two variables since

the thermal electromagnetic radiation emitted by the object itself should be the only radiation source (see THERMOGRAPHY). The principles of fluorescence imaging are similar to those of thermal imaging. In contrast to reflected (also denoted direct) imaging, fluorescence imaging uses a radiation source to excite electromagnetic radiation of a wavelength longer than the incident wavelengths (see PHOTOLUMINESCENCE OF EGYPTIAN BLUE). Subsequently, only the emitted portion of the electromagnetic radiation is recorded.

Most spectral imaging will, however, mainly rely on reflected radiation and only consider (a part of) the near-ultraviolet to short wavelength infrared range, from 315 nm to 3,000 nm. Theoretically, one could say that multispectral imaging starts as soon as data in more than one spectral band are acquired. However, the practical threshold is often four spectral channels, since three wavebands are conventionally acquired by a digital photographic camera and the human visual system (Bianco et al. 2012).

A normal color photograph can be considered a three-dimensional data cube (x, y, λ) in which the first two dimensions (x, y) are the spatial dimensions (i.e., the spatial location of every pixel). The third dimension (λ) is a spectral one. It corresponds to the same spatial position in three unique images, each of them holding the captured reflectance data in one of the three 100-nm-wide spectral bands. Given that these bands generally capture the reflected light in the blue (400 nm, 500 nm), green (500 nm, 600 nm), and red (600 nm, 700 nm) portion of the visible optical spectrum, normal photographs are often denoted RGB images. Every pixel of a common digital color photograph will, therefore, contain three digital numbers at the same location to represent the amount of radiation captured in the three broad spectral bands.

As it extends this traditional trichromatic digital camera approach, a multispectral device digitizes the reflected (and/or emitted) electro-

magnetic radiation in at least four different spectral bands. These bands also constitute a data cube, but one with an extended spectral dimension. This “extension” usually means three different things. First: a multispectral image is no longer a stack of three spatially co-registered images, but at least four or more spectral bands/images are acquired. Second: any of these spectral bands can cover a part of the invisible optical spectrum (be it near-ultraviolet (315 nm, 400 nm), near-infrared (700 nm, 1,100 nm), or short wavelength infrared (1,100 nm, 3,000 nm)). Third: the spectral bands are commonly between 20 nm and 100 nm wide. Although the spectral sensitivities can have a small spectral overlap similar to digital photographic cameras, multispectral instruments very often feature adjacent bands with a small spectral gap inbetween them (e.g., (450 nm, 500 nm), (550 nm, 600 nm) etc.).

Hyperspectral imaging extends this multispectral concept even further. The imagers feature a higher spectral resolution (often a bandwidth of about 10 nm) and capture more and (nearly) contiguous (i.e., adjacent and not overlapping) spectra (van der Meer and de Jong 2001). Although the borderline between multi- and hyperspectral imaging is rather discipline dependent, the threshold is often taken to be 10-12 spectral bands (Shrestha, Mansouri, and Hardeberg 2011). In other words: hyperspectral imaging creates a data cube of tens to hundreds of spatially co-registered two-dimensional images, each of them representing reflected electromagnetic radiant energy in a small and unique spectral waveband. Through a combination of all these single spectral values, every individual pixel of the final hyperspectral image holds the complete reflectance (or emission) spectrum (also denoted the spectral signature) of the object that was sampled at that specific location. Due to this characteristic, hyperspectral imaging is also known as imaging spectroscopy, spectroscopy being the study of the interaction between matter and radiant energy. Recording this spectral signature (and correcting it for the influence of the radiation source) opens up a whole world of unique possibilities for the benefit of heritage.

Applications

From here onward, no further strict distinction will be made between multi- and hyperspectral imaging and the process of capturing, processing, displaying, and interpreting images with a high number of spectral channels will just be referred to as spectral imaging. One just has to remember that the number of spectral bands, their bandwidth, and their spectral overlap can vary.

Archaeologists have used spectral imaging for various reasons, one of them being archaeological prospection. Buried archaeological residues often change the chemical and physical properties of the local soil matrix, and might be revealed by differences in the color or height of vegetation on top of the remains (i.e., crop or vegetation marks) or distinct tonal differences in the ploughed soil (soil marks). Traditionally, detection and documentation of these residues is carried out using conventional photographic methods (see AERIAL PHOTOGRAPHY). However, because spectral images allow for a more detailed assessment of specific and subtle vegetation characteristics (e.g., the red edge response in stressed versus healthy plants) and soil properties (e.g., mineral composition), they can provide more information about subsurface remains, which helps in the efficient detection, mapping, and management of buried heritage. Although numerous spaceborne spectral imaging systems are in existence (see SATELLITE HYPERSPECTRAL AND MULTISPECTRAL IMAGING), airborne multi- and hyperspectral sensors have proven to be more effective means for the discovery and detailed recording of site-level features due to their higher spatial resolution.

However, most heritage-related imaging applications are terrestrial in nature, mainly aimed at documenting or investigating artifacts or excavation profiles. One of the main reasons to use spectral imaging is due to the fact that three-band digital cameras can be considered inaccurate color reproduction instruments since their spectral bands differ from the spectral responses of the human eye. To overcome this, spectral data in more wavebands need to be acquired. In imaging applications where color accuracy is key, spectral images can vary from

four to five broad image channels up to 40 narrow spectral bands. Obviously, more and smaller spectral channels have the potential to digitize the spectral signature better, although mathematical techniques exist to approximate the spectral signature out of only a few spectral bands. Since the 1990s, there have been many studies to determine the amount of (theoretical and real) filters needed for accurate color imaging. Despite the lack of agreement on the minimum amount of spectral bands to achieve this and the related variety in processing steps (e.g., getting rid of the illumination influence), spectral imaging nevertheless enables the storage of color-accurate master copies in cultural archives and digital museums.

Given the possibility to directly assess the spectral signature of objects irrespective of their illumination, this per-pixel spectral information can be used to render the artifact for any given observer or viewing condition. The field of painting conservation exploits this characteristic to simulate how the colors of a painting were perceived under different illuminants such as candlelight and daylight. Because any observer- or illumination-specific rendering should be discounted for a reliable assessment of an artifact, spectral images also constitute essential information for research on monitoring and restoring heritage objects, predicting their appearance after cleaning and assessing possible damage by transportation.

Spectral imaging also makes it possible to distinguish the materials comprising the various objects in the scene. By comparing the spectral response of a region against the spectral response of known features (e.g., pigments and binders), it becomes possible to identify an artist's materials. For instance, this approach could be used to map the dissimilar spatial distribution of yellow ochre and lead-tin yellow pigment at the surface of a polychrome artwork. Thanks to the dissimilar spectral reflectance features of inks, spectral imaging is often used to enhance the reading of old documents. Faded fragments of writing on leather, papyrus, pottery sherds, and clay tablets can frequently be visualized when imaged in the nonvisible ultraviolet and infrared wavebands.

Drawbacks and future research

The drawbacks of spectral imaging revolve around the quantity of data that are gathered. In addition, the acquisition of data in small spectral bands makes the imaging process more noise prone compared to broadband photography. Whereas capturing, processing, and reproduction of standard photographic data can rely on a wide variety of industry-standardized tools, spectral imaging often relies on less widespread and even bespoke infrastructures. That said, a number of hardware configurations can be used to acquire spectral images. In its simplest form, a standard (or modified) digital camera can be equipped with various filters that isolate individual spectral bands. However, most systems are bulkier prototypes developed for individual research purposes, while some very complex systems (certainly in the case of airborne imaging) are produced commercially.

To view and pre- and post-process the huge amounts of spectral imaging data, dedicated software packages are needed as well. As previously mentioned, deriving the actual spectral data from the acquired output requires a major amount of signal processing and differs according to the specific hardware setup. Moreover, dedicated software might be used to mosaic the individual images (e.g., when large objects have to be imaged) or for post-processing operations such as distinguishing pixels based on their spectral characteristics.

In 2016, most spectral imaging systems were still passive (i.e., they record reflected or emitted radiation). However, laser scanning technology could change this situation in the coming decade. Although the majority of airborne or terrestrial laser scanners still operate at one specific wavelength, multi-wavelength laser setups have been in operation since 2010. Their application will certainly be a future hot research topic in the ongoing story of heritage spectral imaging, as the active emission of radiation from laser scanners makes this approach independent of any external illumination.

SEE ALSO: Airborne Laser Scanning and Lidar; Airborne Remote Sensing; Archaeological Photography; Archaeological Videography;

Chemical Mapping; Computational Photography; Imaging; Ink; Multispectral and Hyperspectral Imaging of Artworks; Optically Stimulated Luminescence; Raman Spectroscopy; Raman Spectroscopy in Conservation; Reflectometry; Airborne Remote Sensing; Terrestrial Lidar; Thermoluminescence

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Multispectral and Hyperspectral Imaging of Artworks

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Multi- and hyperspectral imaging consists of the capture of a number of images of the same object in a series of different spectral bands. Multispectral imaging (MSI) is the collection of a few to tens of images in narrow or wide spectral bands which may not be contiguous. Hyperspectral imaging (HSI) is the collection of hundreds of contiguous and narrow spectral band images. Once the images are assembled in a so-called image-cube and radiometrically calibrated—either in an absolute way (spectral radiance) or in a relative sense, so-called band-to-band—they provide spectral information across the entire imaged surface. Therefore, MSI and HSI are often collectively referred to as “imaging spectroscopy” or “spectral imaging.”

HSI cameras have spectral range and spectral resolution similar to bench-top non-imaging spectrometers. For this reason, imaging spectroscopy has become largely synonymous with HSI since the focus is on acquiring spectral content—reflectance spectra or fluorescence spectra—across the surface of an object. MSI can also provide useful spectral information about objects made up of few materials that can be distinguished using a small number of spectral bands. HSI is designed for the more general cases where the materials are unknown or have highly varied spectra.

The primary benefit of imaging spectroscopy is that it allows the rapid collection of bench-quality spectra across a large area. Such large datasets are

organized as 3D data-cubes where the 2D images acquired in each spectral band are “stacked” according to central wavelength or wavenumber. Thus one can retrieve the spectral information for any pixel in the imaged scene and compare it to spectral databases or to spectral data from other pixels in the scene.

Imaging spectroscopy has proven most useful in separating areas of the imaged scene into clusters of materials having the same spectral features. Such features can be used to identify materials directly, or at least to define areas to be further studied with more sensitive analytical methods for materials identification, such as Raman or Fourier transform infrared (FTIR) spectroscopy. The classification of the spectral data can be done either manually or automatically.

The spectral range over which MSI and HSI are performed depends on the materials one is interested in spatially separating (classifying), and ideally identify from the spectral features collected. The most used spectral regions are the visible (400–700) and near-infrared (NIR) (700 to ~2,500 nm). These ranges provide rich information associated with electronic transitions that give rise to color, as well as combination and overtone vibrational features—in the NIR—which often provide unique material identification. They also allow penetration of the outer paint layers, providing information about subsurface layers. While the mid-IR range (3–11 μm) offers rich vibrational spectral features, it requires more complex and costly instrumentation. Additional drawbacks include spectral distortions due to reflectance-mode spectroscopy, limitations in the depth of penetration, and the need for a thermal source.

Imaging spectroscopy (as HSI) was first developed in the mid-1980s for remote sensing of the Earth's surface (see SATELLITE HYPERSPECTRAL AND MULTISPECTRAL IMAGING); in subsequent years its application was extended to numerous other fields of research such as environmental monitoring and quality control of food and other natural products.

Since the beginning of this century, imaging spectroscopy has been increasingly used to study artworks, especially low-relief polychrome objects such as easel and wall paintings, as well as works on paper and parchment (Cucci, Delaney, and Picollo 2016; Liang 2012). These have included mostly small-scale objects measuring from a few centimeters across to approximately 2 m²; spatial sampling typically ranges from 100 μ m to a few millimeters.

The reasons why imaging spectroscopy is used to study works of art mirror those showing why this method has been successful in other fields of research: making material maps, in this case maps of artists' materials, including pigments and paint binders, fibers in historic textiles, and different types of plastics, finding non-original materials and retouched areas, monitoring degradation, and assessing cleaning and restoration treatments. A slightly more unusual application regards the visualization of information which is hidden underneath the paint layers, such as preparatory sketches ("underdrawing") as well as *pentimenti*, that is, compositional changes made by an artist between the drawing and the painting stage, often unnoticeable with the naked eye. Examples of each of these applications are briefly presented in this entry.

Spectral imaging systems suited for the analysis of artworks usually consist of the following essential components: (1) suitable lighting both in terms of spectral range covered and of acceptable light levels for the work of art; (2) an imaging objective, typically well corrected over the spectral range of interest; (3) a single-element detector or 2D detector array with good sensitivity in the spectral range of interest; (4) a dispersive spectral element, that is, a means of wavelength selection; and (5) a radiometric calibration source or reference target.

These essential components can be combined in a variety of ways to assemble a useful spectral imaging camera system. Choices to be made include where to make the wavelength selection—that is, on the illumination light path or after the imaging lens—and what type of dispersive element to use. Spectral interference filters offer one of the simplest multispectral systems that allows tailoring the spectral range each time for the particular question at hand. Imaging spectrometers offer the largest spectral resolution and

number of spectral bands, but require a longer acquisition time as they typically have much narrower spectral bands. The most time-efficient systems are imaging spectrometers that provide spatially resolved spectral information along the slit of the spectrometer.

The instrument's design usually depends on the specific goals to be achieved. For example, a researcher seeking to separate a limited set of pigments on a large or highly detailed work of art might utilize a system with a series of interference filters and a high spatial resolution camera. Investigators studying artworks with a large range of unknown pigments would find a camera having lower spatial resolution but broader spectral range and higher spectral resolution the most useful. In this case, a scanning imaging spectrometer able to capture hundreds of spectral bands at once would be ideal.

The MSI and HSI protocols used to study artworks consist of several steps, which can be broadly classified as image acquisition, calibration, and processing. A key step during post-processing of image-cubes, which is often overlooked but has an effect on the choice of imaging setup, is the need for some sort of spatial registration for interference filter systems, or even for systems using spectrally filtered lights with lenses without adequate color or chromatic aberration correction. Imaging spectrometers do not suffer from spatial registration issues, but care needs to be taken to ensure light levels are acceptable for the work of art under study.

Recent notable applications of imaging spectroscopy to the study of artworks include the identification and mapping of pigments in Pablo Picasso's *Peonies* (Delaney et al. 2016a). HSI in both reflectance and luminescence mode was used to reveal a wide range of pigments comprising vermilion, cadmium yellow, cobalt blue, Prussian blue, and an organic red colorant. The additional presence of emerald green and zinc white was confirmed by further analysis by X-ray fluorescence (XRF) spectroscopy and fiber-optic reflectance spectroscopy (FORS). As a matter of fact, spectral imaging is often used in combination with site-specific spectroscopic methods to provide more secure identification of artists' materials. Considered alone, the reflectance and/or luminescence properties of pigments

and binders in the visible and NIR range, while sufficient to separate them, do not always allow their secure identification.

Mapping paint binders is especially challenging due to their subtle spectral features in the NIR, which shift and decrease in intensity with aging. Using an exceptionally sensitive NIR imaging spectrometer, Ricciardi et al. (2012) were nonetheless able to map the selective use of a lipid-containing binder (likely egg yolk) in a fifteenth-century illuminated manuscript fragment.

A similarly sensitive instrument was used to identify sections of two sixteenth-century tapestries woven with silk and wool fibers, respectively (Delaney et al. 2016b). In both cases, the study revealed a correlation between the colorants (identified by FORS) and the fibers used in each area. In the red areas of one of the tapestries, for example, wool fibers were dyed with a plant-derived dye (madder), while silk fibers were dyed with an insect-derived dye (Old World cochineal).

Modern materials found in twentieth-century museum objects can also be analyzed using MSI and HSI. Cséfalvayová, Strlič, and Karjalainen (2011) demonstrated the potential of NIR imaging spectroscopy for the quick assessment of large collections of such works of art by building an extensive database of reference objects and spectra and using it to distinguish between different types of historic plastics.

NIR imaging spectroscopy can also be used to improve upon “classic” broadband infrared reflectography. For example, the multiple compositions known to exist beneath the surface of Pablo Picasso’s *The Tragedy* were most clearly revealed by selecting spectral bands offering the maximum contrast for each. Images collected at approximately 1,200, 1,350, and 1,500 nm, respectively, allowed optimal visualization of underdrawing for the final composition, a dying horse present in an earlier sketch for a different painting, and a series of caricatures drawn directly on the wood panel (Delaney et al. 2016a).

As imaging spectroscopy rapidly becomes an indispensable tool for conservators and heritage scientists, its combination with other chemical imaging methods continues to enhance the information it can provide. For example, visible and NIR HSI (400–1,680 nm) used with macro-XRF

scanning provided robust identification and mapping of pigments and binding media, as well as the visualization of a preparatory design, in a painting by the Italian Renaissance artist Cosimo Tura (Dooley et al. 2014). A recent review of hyperspectral methods that can be used to image artworks at a macroscopic level describes exciting developments in the use of macro-XRF and macro-XRD scanning, computed X-ray laminography, mid-IR hyperspectral imaging, and optical coherent tomography in NIR (Legrand et al. 2014).

SEE ALSO: Conservation Science; Imaging

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Optical Microscopy

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Optical microscopy (OM) is often also called light microscopy, as it is based on a focused beam of light for the examination of samples through a system of lenses. It is one of the earliest and still most commonly used examination techniques for scientific investigation, and is frequently used in the research of archaeological materials.

OM has numerous applications. Most important is the determination of the constituents and microstructure of materials. These can be different phases in metal alloys, different minerals in petrographic samples (see PETROGRAPHY AND CERAMICS), different pigments and layers in painting works (see GLAZES, SLIPS, AND PAINTS), or cells in biological samples (see USE OF BIOLOGICAL COLLECTIONS). Such observations are of practical importance since the structure and constitution of a material has implications for its physical and chemical behavior, and its conservation (see CONSERVATION), and can inform about the nature and origin of materials, as well as about materials and manufacturing techniques that were in use in the past.

Frequently, examination by OM precedes other analytical techniques such as X-ray fluorescence (XRF) (see X-RAY FLUORESCENCE SPECTROMETRY (XRF)), X-ray diffraction (XRD) (see XRD AND MATERIALS ANALYSIS), scanning electron microscopy (SEM) (see SCANNING ELECTRON MICROSCOPY), Raman spectroscopy (see RAMAN SPECTROSCOPY), or Fourier transform infrared (FTIR) spectrometry (see INFRARED ABSORPTION SPECTROSCOPY (IR, FTIR, DRIFT, ATR)), since it allows a broad and preliminary knowledge of the structure and nature of materials in a relatively inexpensive way.

There is an endless array of optical microscopes with different options and configurations available for investigation. Each one has specific advantages for different types of materials.

Equipment

Microscopes can be designed for illumination with incident (reflected) light or transmitted light. The former are commonly called metallurgical microscopes since they are used for observation of metals or ores (see ORE AND SMELTING SLAG) which are opaque. The latter are usually used in mineralogical and biological studies, since samples can be transparent to translucent. A dual-purpose microscope is capable of viewing samples in reflected as well as in transmitted light.

Based on the structure design, there are two basic types of microscopes: the upright microscope and the inverted microscope (e.g., see Figure 1). The difference relies on the orientation of the face of the polished (prepared) specimen that is being examined.

Essentially, the constitution of a microscope can be abbreviated to a light source, a condenser system, light filters, objective lens, eyepieces, and a stage. A digital recording camera is frequently attached, to allow images to be captured and treated digitally.

Various light sources are available, such as LED, halogen, xenon, Hg, and tungsten lamps. Differences can be in the intensity of the light, the quality of the continuum visual spectrum, and the possibility of obtaining monochromatic radiation.

The condenser system is an adjustable lens placed in front of the illumination system. It serves to source the illumination to a desired optical path, being capable of modeling the light trajectory and intensity by field and aperture diaphragms.

The use of filters is often required to modify the incident light and allow optimum examination of the specimen. Filters can reduce the intensity of incident light across the entire visible spectrum or they can act as selective filters, by absorbing certain wavelengths (colors). They can also act by polarizing the light, allowing the transmission of light that only vibrates in one direction.

The objective lens is the essential component of the microscope which forms the primary image

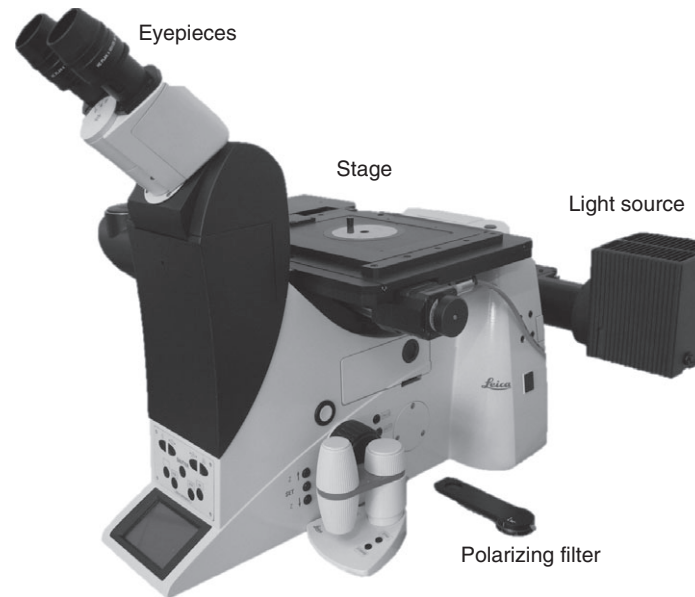


Figure 1 An inverted (motorized) metallurgical optical microscope (DMI5000M, Leica) suitable for reflected light observations. The large stage allows large samples or artifacts to be examined. A polarizing filter is placed next to the microscope.

of the examined specimen. It collects the reflected or transmitted light and combines it to form the image. The quality of the lens is thus of major importance for the quality of the final image. Many types of lens defects affect the sharpness of the image obtained, for example astigmatism, and chromatic and spherical aberrations. Various objective lenses exist on the market that correct some of these defects. Apochromatic lenses correct more chromatic aberrations than achromatic lenses, but are more expensive. A compromise is the semi-apochromatic (or fluorite) objectives, which can be found in many microscopes. Flat-field corrected objectives, called plan objectives, and are especially suited for the use of charge-coupled device (CCD) cameras. Lenses can be designed to be used with air or oil as the medium between the sample and the objective front lens. The latter provide a better image, but require more care in operation and are thus not so commonly used.

In a microscope, four to six objectives are usually mounted on a rotating nose-piece turret. Each objective has a specific magnification number (typically 5 $\times$, 10 $\times$, 20 $\times$, 50 $\times$, 100 $\times$) and

a different working distance. Thus, when switching from a low-power objective to a high-power objective it is necessary to finely refocus the image by adjusting the height of the stage where the specimen is placed. As a rule, as the magnifying power of the objective increases, the working distance decreases, resulting in the sample being closer to the front surface of the objective lens.

Each objective has a numerical aperture (NA) which is a measure of the light collection capability. The NA is given by the sine of half of the aperture angle of the objective and takes into account the refractive index of the medium between the objective front lens and the sample. Its value affects the ability to resolve fine specimen details. The depth of field in OM is typically very limited, and can only be slightly improved by reducing the NA of the system: by closing down the aperture diaphragm and/or using a lower NA objective.

The eyepiece (ocular) allows the user's eye to obtain full resolution of the objective by further magnifying the image produced by the objective. Usually, eyepiece magnification is 10 $\times$. The total magnification of the produced image is thus the product of the magnification of the objectives and the eyepiece.

The mechanical stage of the microscope is where the sample is placed and focused on. Stages allow movement in x, y, and z axes. In mineralogy and petrography, circular stages are frequently used to also allow measurements of the angle of rotation, important for polarized-light work.

Methods and uses

Since the beginning of this century, partly because of rapid improvements in hardware and software, a large variety of microscopy and imaging (see *IMAGING*) solutions have become available. Microscopes with motorized components connected to a computer with specific software can take advantage of multistep routines for the development of further visualization modes. One example is the confocal fluorescence microscopy which uses a pinhole to eliminate out-of-focus signal and is capable of reconstructing 3D (tomographic) models (see *COMPUTED TOMOGRAPHY*) of translucent biological samples. Another is the multifocus imaging technique, which considerably extends depth of field of an OM image by overlapping focused portions of successive images taken along the z-axis. The latest technique allows the examination of non-planar surfaces, avoiding conventional sample taking and preparation (of some interest in the study of cultural materials (Figueiredo et al. 2013)), and allows for the study of topographic features by applying 3D surface modeling tools (e.g., Image J software (Rasband 2018)).

In OM, besides primary brightfield illumination, a wide range of illumination options can be used for enhancing contrast. These include darkfield illumination, polarized light, phase contrast illumination, interface techniques, and various filters.

Darkfield illumination (obtained by allowing only oblique rays of large angles to strike the specimen) produces an intensity contrast image accentuating surface irregularities, such as grain boundaries, cracks, and pits. Polarized light (obtained by applying a polarized filter) is very useful for the observation of constituents by their characteristic (polarized) colors, and allows the use of crossed polars mode for the identification of anisotropic crystals. In crossed polars mode, a substage polarized filter (polarizer) and an

above-stage polarized filter (analyzer) are aligned at right angles to each other.

Since certain materials emit radiation of their own when illuminated by ultraviolet or other specific wavelength, the use of monochromatic light can be useful for the identification and structural examination of materials. Microscopes that allow such observations are frequently called fluorescence microscopes, and are commonly used in biological-based materials.

For OM observation a sample should typically have a plain polished surface, as free as possible of pits, scratches, and fractures. This is achieved by grounding and polishing the surface with progressive use of finer and finer abrasives. To allow the handling of the sample it can be mounted in epoxy resin; the mounting also facilitates future sample storage. In some cases, chemical etching (by the application of a suitable etching solution to the polished surface of the sample, normally by immersion) can be performed to reveal the structure. Examples are to detect coring/zoning, twinning, grain boundaries, and for enhancing phases in both metal and mineral samples. In biological samples, etching can also be performed; thin sections of wood can be etched and examined for identification of cell anatomy, enabling the identification of species (Schoch et al. 2007). Additionally, some organic materials can be stained with certain dyes (fluorochromes) to produce fluorescence.

When studying multilayered structures or textured polycrystalline materials, the location of sampling and sample orientation (see *SAMPLING THEORY*) are of major importance to obtain meaningful data. In the case of paintings (e.g., murals, rock art, and paintings on ceramics), sampling should ideally include all the painting layer(s) and the ground material. Observation of the cross-section will allow the study of thickness and number of painting layers, and the size and shape of pigments, and evaluate adhesion to the ground material, providing information on materials used and technical skills in ancient societies.

Studies on ceramics or petrographic samples are frequently made in thin sections (ca. 0.03 mm thick), using transmitted light due to the presence of transparent to translucent minerals. However, if opaque constituents are present, reflected light can also be used. In both cases, the use of polarized light for mineral and ore identification

is desirable (since transmitted light produces superior contrast-enhancing polarizing images, it is preferably used rather than reflected light). For example, hematite and cuprite can be seen as gray when viewed in reflected brightfield illumination or as deep red in polarized light (due to internal reflections), but hematite shows very distinct gray-blue and gray-yellow colors on twin boundaries in crossed polars (Ineson 1989). During OM examinations, the identification of temperature-sensitive minerals can provide information on firing temperatures of ceramics, and the identification of particular minerals or textures can indicate the provenance of the raw materials.

The study of archaeological metals can benefit greatly from OM examinations (see METALLOGRAPHY). Reflected brightfield illumination and polarized light allows the distinction among different phases, and also an evaluation of corrosion (see DETERIORATION). If metal phases are clearly identified it is possible to estimate the alloy composition by image analysis. The size and morphology of grains allows inference on the cooling rate of the metal, as well as reconstruction of thermomechanical processes to which the object was subjected during shaping. By etching samples with face-centered cubic (FCC) structures (e.g., copper, lead, and silver), twinning grains can be evidenced, which indicates plastic deformation prior to an annealing (thermal) treatment. Finally, the metallographic information can provide important data about the development of metallurgical skills at different periods and in different regions.

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Paleoenvironmental Reconstruction

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While analyses of the tangible remains of human behavior are critical to the exploration of past societies, it is also of paramount importance to understand the environment(s) and landscape(s) people dwelt within. Paleoenvironmental reconstruction describes a range of multidisciplinary approaches involving varying methodologies, data types, datasets (groupings of observations based on a goal or target, with clear measurement parameters, and organized in terms of a specific problem), and theoretical positions. This research focuses on three key elements: the physical, biological, and social environments in which people existed; the ecological relationships between humans and their environment at a particular place and time; and the evolution of linked physical, biological, and social systems over varying durations of time and scales of space. The goal of much paleoenvironmental reconstruction is to approximate past human habitats (typical environments or territories, sometimes referred to as a “target environment”) to understand the potentials and limitations encountered during a human lifespan (Dincauze 2000, 7, 20–23). This research also facilitates exploration of the human role within a larger milieu (i.e., the human niche; see Evans and O'Connor 1999, 27), and the ways in which human systems navigated and negotiated instability or dynamic change in their surroundings.

Paleoenvironmental reconstruction is practiced largely by environmental archaeologists, but often requires input from a wider range of subfields (e.g., zooarchaeology (see ZOOARCHAEOLOGY), geoarchaeology (see GEOARCHAEOLOGY), paleoethnobotany (see PALEOETHNOBOTANY), archaeometry (see ARCHAEOMETRY), bioarchaeology (see BIOARCHAEOLOGY)) and disciplines

(e.g., palynology (see PALYNOLOGY), botany, biology, ecology, geomorphology, pedology, geology, climatology, oceanography). Initial interest in paleoenvironmental reconstruction for archaeological investigation can be traced to northern and central European (especially Scandinavian) archaeologists in the nineteenth and early twentieth centuries. Pioneering archaeologist Jens Worsaae collaborated with biologists and geologists to develop paleoenvironmental settings within which he believed archaeological remains should be situated (Trigger 1989, 80–82). Graham Clark's research at the site of Star Carr, UK, built inferences of Mesolithic hunter-gatherer economic and social behavior upon reconstructions of the post-glacial landscape using waterlogged deposits and evidence from faunal, vegetal, and mineral remains (Clark 1954). In the United States, Julian Steward's multilineal, cultural ecology approach focused closely on environment as a driver of human behavior and change, and catalyzed important environmentally underpinned research in the 1960s and 1970s by scholars such as Karl Butzer, Kent Flannery, and many others. Such environmentally driven research precipitated the archaeological specializations of zooarchaeology, archaeobotany, and geoarchaeology (among others), specializations that are widespread today. Formation of the Association for Environmental Archaeology (AEA) in 1979 formalized this arena of study, as did the success of the AEA's peer-reviewed journal *Environmental Archaeology*, now in its twentieth year of publication.

The strength of this multidisciplinary approach—primarily that it integrates the methodological and analytical strengths of well-developed and theorized fields to obtain robust reconstructions—is accompanied by some inherent limitations. It is often difficult to integrate the theory, research goals, and methodologies of specialists from diverse fields. Projects involving many scientists must be conscious of the increased potential for inferential and explanatory mismatch, and of the uncertainty and error generated by incompatible frames of

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reference and data incorporation. Reconstructions that successfully incorporate a diverse array of complementary data types (those configured at congruent temporal scales and derived from similar geographical locations) benefit enormously in robusticity (increased confidence that the reconstruction is accurately modeling the target environment in the past). Dataset consistency is also crucial, as all datasets should support a similar reconstruction scenario; mismatch between datasets is an indicator that one or all of the sets must be further evaluated. Strong paleoenvironmental reconstructions must strike a balance between the type, quantity, and quality of data incorporated into useful and compatible datasets (Dincauze 2000, 24–26).

Another inherent issue in paleoenvironmental reconstruction relates to inductive barriers imposed on researchers. While the primary goal of this research is to achieve the most probable representation of a target environment, it must be acknowledged that even the most detailed reconstructions are nothing more than multiple working hypotheses that generate a model, simulacrum, or best guess about past human habitats, and are supported by the most appropriate and current data available. However, researchers can never be certain how close they are to approximating the target system. Further, much paleoenvironmental research incorporates considerable amounts of proxy data, quantitative and qualitative values that indirectly inform researchers about past environmental conditions that have not been preserved or cannot be directly observed through currently observable data. Researchers must be vigilant when using proxy data, as too much reliance may lead to a false sense of reality and even tautological reasoning. Advances in archaeological taphonomy (see TAPHONOMY) have helped to alleviate some of these inferential issues, strengthening understandings of the impact of past natural, physical, and biological processes on the archaeological record. However, the issue of equifinality (different causal factors and processes leading to a similar observable end state) must be addressed, in addition to the acknowledgment that past environments are comprised of myriad agents and forces linked in a multitude of complex relationships, and that straightforward analogy cannot necessarily be assumed (Williams and Jackson 2007).

Paleoenvironmental reconstructions undertaken for archaeological purposes vary greatly in spatial scale, scope of environmental variables, and temporality. Each reconstruction is therefore unique in its construction and intended product. As available and accessible data will affect the end result most greatly, data from all four Earth spheres should ideally be included (atmosphere, hydrosphere, lithosphere, and biosphere). However, data from these spheres differ in type and longevity, and require very different collection strategies, analytical procedures, and theoretical frameworks.

Many paleoenvironmental reconstructions begin with a strong foundational understanding of the abiotic circumstances of the physical landscape. This is a difficult step, given that landscapes are dynamic entities. Geomorphology, geology, and sedimentology provide the primary sources of evidence. Coring (see CORING), augering (see AUGERING), remote sensing (see AIRBORNE REMOTE SENSING), electrical resistivity (see ELECTRICAL RESISTIVITY), magnetometry (see MAGNETOMETRY), and ground-penetrating radar (see GROUND-PENETRATING RADAR) are key methodological tools that facilitate investigation of the terrestrial and marine subsurface. Such research provides direct evidence about the evolution of landscape features and should be underpinned by sound sampling strategies (see sampling theory (see SAMPLING THEORY), sampling in geoarchaeology, and geomorphological survey (see GEOMORPHOLOGICAL SURVEY)). Knowledge of sediments, soils, sedimentation rates and processes, and soil development are important, as is the inclusion of information about broader geological processes such as glaciations (and associated forces of isostasy), geophysical events (earthquakes, tremors, volcanic eruptions), and oceanic changes (eustatic and global sea-level change). Modern computer applications such as geographic information systems (GIS) have facilitated the harnessing of such wide-ranging datasets. Maintaining complementarity, consistency, and scalar congruence among and between these datasets is of critical importance during the design and development of any paleoenvironmental reconstruction. To obtain detailed diachronic models of past physical landscapes that can be used to investigate human questions and processes, archaeological modelers

must allocate additional effort toward correlating geophysical and geological data with the human spatiotemporal scale, which is generally narrower in spatial extent and contracted in time.

Subsequent to the generation of sufficiently detailed physical landscape reconstructions, the next procedural step generally involves superimposing and integrating biota, including vegetation, fauna, and, of course, *Homo sapiens*. There are many sources of direct evidence from which information about such environmental components can be drawn, and methods and techniques from various biological subdisciplines are often incorporated. Palynology, the study of pollen grains and spores, is analytically well developed and can yield far-reaching inferences about plant distributions and successions, not to mention proxy evidence about environmental modifications (natural or cultural). Botanical microfossil (phytolith analysis (see PHYTOLITH ANALYSIS) and starch granule analysis (see STARCH GRANULE ANALYSIS)) and macrofossil research is also developing a robust methodological practice, and should add complementary evidence to palynological results (see Pearsall 2015, and others). These archives of natural data, in addition to tree-ring and isotopic analysis, can provide information about climate and climate change in the ancient atmosphere, the ongoing dynamics between the lithosphere and hydrosphere, and the timing, tempo, and cadence of such changes. For example, biotic data such as the initiation of peat growth, present in geomorphologic cores of the subsurface, indicate changes in both the lithosphere and hydrosphere (sea-level rise and inundation of previously above-water landform features), as well as global atmospheric changes in solar radiation, trace elements, wind patterns, and precipitation and moisture levels.

Direct evidence from vegetative sources have proven to be incredibly instructive for understanding faunal distributions, habitats, and territories, migrations, and speciation and extinction events. Inferences are greatly strengthened when complementary direct evidence can be obtained from the animal micro- and macrofossil record (diatom and foraminifera analysis (see DIATOMS), land and freshwater molluscs (see LAND AND FRESHWATER MOLLUSCS), marine molluscs (see MARINE MOLLUSCS),

ostracods and cladocerans (see OSTRACODS AND CLADOCERANS), and insects (see ARCHAEOENTOMOLOGY)). The importance of biotic data in paleoenvironmental reconstruction undertaken for archaeological purposes lies in its congruency with the human spatiotemporal scale (most plants and animals share a similar scale of existence to humans). More problematic are the issues of consistency between various direct and indirect lines of biotic information, and the question of how many such biotic datasets to incorporate into a reconstruction to achieve maximum complementarity and diversity without bogging down the tools used to synthesize the information (i.e., the geospatial software and computer hardware). Furthermore, no paleoenvironmental reconstruction is complete until our own species, *H sapiens*, or our ancestors, have been added to the mix. Human actions are typically considered as part of biospheric processes, although some argue the Earth has entered an entirely new epoch (the Anthropocene) with a new and growing Earth sphere (the Anthrosphere), in which the impact of one biological species is increasingly impacting the conditions of the other integrated spheres (e.g., in creating climate change that leads to glacial retraction, rising sea levels, and changes in the geophysical landscape and biotic communities at a worldwide scale) (Crutzen 2002). The primary source of data about the human component of the environmental system derives from archaeological data.

Throughout this process, consideration of climate and climate change should be made, as the conditions of the atmosphere impacted the physical landscape and biotic communities in both the short and long term. While much can be learned by proxy about the past climate from the physical landscape (presence of landform features and analysis of pedogenesis and diagenesis) as well as biotic data (data derived from studies of dendrochronology, palynology, diatoms, phytoliths, and macrofossils), it is helpful to reference data from other sources. For example, ocean sediment and ice cores can yield valuable information (in the form of benthic fossils and elemental ratios of inorganic sediments) about temperature swings, changes in the moisture content of air masses, and the patterning of winds and storms. Periodic consideration of climate for a given place in time, and investigation of the dynamics

of climate change, is critical for building a robust paleoenvironmental reconstruction. One recent research initiative that built such reconstructions is the Interdisciplinary Archaeological Research Program carried out at the Maasvlakte 2 Harbor in the port of Rotterdam, the Netherlands (Moree and Sier 2015). The resulting paleoenvironmental scenarios revealed ecologically dynamic, resource-rich river dune complexes that were utilized by Mesolithic hunter-gatherer-fishers for thousands of years.

Paleoenvironmental reconstruction has primarily been used as a methodological tool within the archaeological science toolkit, to “set the stage” for deeper probing of the human condition, ostensibly the more interesting and rewarding end goal. Today, however, advances in data collection and computer technologies are permitting researchers to heuristically investigate broader questions about nonlinear human behaviors, decision-making, and cultural processes through their paleoenvironmental reconstructions. Archaeological applications of this research are becoming increasingly valued for their contributions to the biological and earth sciences. While archaeological datasets are incomplete and oftentimes biased by research, preservation, and/or collection strategies, they have the potential to shed light on much longer-term ecological processes. The growth in more specialized environmental archaeology journals (such as the *Journal of Island and Coastal Archaeology*, *Geoarchaeology*, and *Archaeometry*) (see O’Connor 2001) as well as “cross-over” journals that regularly publish archaeological research (e.g., the *Anthropocene*, the *Holocene*) attest to this fact. Additionally, the increase in environmentally focused archaeological graduate programs of study (University College

London, University of Sheffield, Umeå University, University of Florida, University of North Texas, Texas A&M University, etc.) indicate that archaeological interpretations underpinned by sound paleoenvironmental reconstruction stand to offer invaluable insight about environments that may not have a current analog, but which may arise in the future.

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Parallel and Distributed Computing

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Parallel or distributed computing is the action of splitting the execution of a computer program into different simultaneous tasks. The main goal behind this decision is to speed up computationally expensive processes that would take too much time with a single computer.

The popularization of parallel computing has been one of the most important recent developments in computer science. This increasing trend is based on two key advances in the field. First, the first decade of the twenty-first century saw the commercialization of cheap commodity computers with multicore architectures. This change in design meant that standard desktop computers integrated more than one central processing unit (CPU) (currently two or four cores). Second, the development of software able to run tasks in parallel was facilitated by the publication of new protocols and platforms. These tools widened the audience of parallel computing by allowing nonspecialized programmers to exploit the new multicore capabilities. These contributions in hardware and software systems extended the application of parallel computing to a vast array of problems with high computational requirements (Dongarra 2006).

Generally speaking, current parallel computing methods offer a diversity of solutions to the need for high computational requirements. In its basic form they allow any developer to accelerate the execution of computationally expensive algorithms by using a desktop computer. The most advanced methods and hardware infrastructures are able to run in a matter of hours simulations that would take years with a single computer.

The simplest form of distributed computing is shared-memory parallelism. It splits a global program into different tasks executed in the CPUs

of a single multicore computer. The cores are integrated in the same machine, and for this reason they can communicate with each other by sharing information. Shared-memory distribution used to be strongly dependent on particular architectures, but standards such as OpenMP and POSIX have currently made source code independent from the hardware where it is being executed. These standards allow a developer to distribute a program while preventing synchronization issues between the different tasks (e.g., a variable being simultaneously modified by two tasks). A special case of shared-memory distribution is the use of graphical processor units (GPUs). GPUs are designed for graphic processing and integrate thousands of very small processors. While CPUs are general-purpose cores that can execute any type of problem, GPUs are extremely efficient for vector-based operations such as the ones undertaken in 3D processing and machine learning.

Shared memory parallelism is limited by the number and speed of the cores inside a computer node. Any improvement in one of these two factors carries with it a significant increase in the price of the hardware. This cost has a dramatic impact on the scalability of the systems, as the investment needed to handle problems of higher complexity will be prohibitive for most institutions.

Distributed memory is an alternative approach used to parallel computing. It consists of a network of CPU cores with independent memory (i.e., each core can only access its own memory). A system created with this method is able to deal with highly complex problems by increasing the number of nodes connected to the network. However, this scalability comes at a price in terms of software development, as the application needs to organize data-sharing as CPUs cannot directly access information owned by the rest of the computer nodes in the network. A protocol called message passing interface (MPI) is the most popular method to implement this communication. The use of this standard ensures that a program running distributed memory parallelism is platform independent and can be executed in any existing architecture.

Both approaches (shared memory and distributed memory) can be combined in systems implementing hybrid parallelism. Its general design integrates several multicore computer nodes within a common network. The entire system is then used to run software implementing both types of parallelism (e.g., using both OpenMP and MPI protocols). The approach is able to efficiently use all available cores while having high scalability.

Hybrid parallelism is the current standard for applications with high computational requirements. The approach can take many forms depending on the communication network linking the computer nodes. The slowest networks are generally defined as grid computing infrastructures. The nodes comprising this network are connected via standard Internet communication. This solution is cheap and reliable, but it can have significant speed bottlenecks as communication speed is much lower than computing speed up to the point where it could be slower than sequential execution. High-performance computing (HPC) architectures are infrastructures designed to minimize these efficiency issues by integrating the computer nodes within a high-speed communication network. The largest and fastest HPC systems are called supercomputers. They combine the power of hundreds of thousands of CPUs or GPUs in large-scale facilities. These cores are integrated within computer nodes connected by networking systems such as InfiniBand. These high-speed networks ensure that communication between nodes is hundreds of times faster than the Ethernet systems used in standard local networks.

Parallel computing has boosted the use of simulation in scientific research. The increase in computing power has allowed a diversity of fields to deal with more complex problems than were previously explored. Systems that were previously modeled at a single level can now be studied with multiscale simulations. This flexibility allows the researcher to link behavior defined at very small resolutions with global dynamics observed in the studied system. Results improve the understanding of topics as diverse as molecular interactions, contamination dispersal, and epidemic spreads.

Archaeological research has employed parallelism to increase the speed of computationally expensive quantitative methods (see SIMULATION MODELING). Popular spatial analysis

such as cumulative viewshed analysis (see VIEWSHED ANALYSIS) and least-cost path calculations (Llobera et al. 2010) are among the most demanding techniques because they are greedy algorithms. The cost and time required to apply these techniques to particular case studies grow exponentially over the size of the region under scrutiny and the resolution of available data. Data resolution has gradually improved during the last years, but it is difficult to exploit this increase in data quality to generate more accurate results because the time required to run the algorithms is excessive for standard computing. The only solution to this challenge beyond reducing the area or the resolution is to boost up computation time using HPC systems.

Computer simulations and especially agent-based models (ABMs) are arguably the method with the highest computing requirements used in archaeological projects. These requirements are often high for ABMs due to a variety of reasons, including large populations of agents, intensive use of multiple datasets, and complex decision-making processes (Rubio-Campillo 2015). While these issues can affect any model, the most generalized challenge by far is the limitation on the number of simulations that are run for a specific experiment. Simulations are typically explored by changing the values of the input parameters and analyzing under what extent the modeled system reacts to these changes. If the model is stochastic then it also needs to be run multiple times for each set of parameter values because every run will have slightly different outcomes. This process requires anywhere from thousands to millions of runs, depending on the complexity of the examined model, and if it is not properly addressed the analysis of the model will be flawed. As a consequence, limitations on the computational resources can seriously impair the results of a simulation, and this is the reason why most efforts on parallelism within the discipline have been linked to simulation.

The advantages of parallelism for research are not limited to speeding up simulations. The popularization of distributed architectures has contributed to the current popularity of machine learning. This family of algorithms allows the user to train the computer to identify concepts based on predefined categories. The most advanced methods such as deep neural networks would

not be possible without the use of clusters of computers working some type of parallelism. This combination of HPC and machine learning is at the core of the current big data revolution where massive datasets are analyzed to identify large-scale behavioral patterns of complex systems (Upadhyaya 2013).

Current research on parallel computing is focused on decreasing different aspects of its functional cost. For example, the constant increase in the number of computer nodes is generating high energy costs and carbon footprints for state-of-the-art HPC infrastructures. Systems using more efficient CPUs are being developed in order to create green supercomputers (Feng, Xizhou, and Ge 2008). At the same time, automatic code generation and out-of-the-box solutions are lowering the technical barrier of parallel programming. These advances will allow any programmer to develop efficient distributed code, thus extending the impact of parallel computing to any challenge requiring high computational resources (Karlin et al. 2013). It is expected that archaeologists will benefit from these improvements and specifically from the decrease in the need for specialized programming skills. If this can be achieved then projects using simulation and similar computationally demanding methods will be able to develop adequate solutions to their CPU requirements. As a consequence, there will be improvements in both the quality of the analysis and the popularity of these tools within archaeological research.

SEE ALSO: Computer Applications in Archaeology; Statistics and GIS

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FURTHER READINGS

Photorealism and Digital Reconstruction

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Reconstruction: a definition

The word “reconstruction” can be defined as the process of bringing something back to its original state. For example, the reconstruction of a collapsed building would mean that all conditions that existed during the building of the first structure are the same during its recreation; the builder is the same, and s/he has access to all the original materials and knows their exact position in the original structure. If any of these parameters do not apply, then the new building is only a construction in the present providing an impression of how the original looked. This is a simplified example to show that the term “reconstruction” is loaded with a meaning that cannot be supported, at least in archaeological contexts.

The notion of reconstruction did not appear in archaeology with the advent of computer applications (see *COMPUTER APPLICATIONS IN ARCHAEOLOGY*). Since the establishment of archaeology as a discipline, archaeologists have been trying, through fieldwork, study, analyses, syntheses, and interpretations (see *INTERPRETATION*), to reconstruct aspects of past reality which not only are limited to objects and architecture but also include social and cultural process and products. However, life in the past, and especially in prehistory in which written accounts do not exist, cannot be deciphered by people who live and act in distant chronotopes. In other words, archaeologists’ interpretations are formed and negotiated through a series of biases and perceptual leaps due to the different spatial, temporal, and cultural contexts that contributed to the formation of past lifeways and structures. Nevertheless, archaeologists were always trying

to produce reconstructions, and all the media used to realize these, such as text, photography (see *ARCHAEOLOGICAL PHOTOGRAPHY*), and illustration provide a distorted reflection of the past since they attempt to convert the three-dimensionality of the world into a two-dimensional production.

The introduction of scientific methods during the processual phase of archaeology in the 1960s enforced the notion of reconstruction. It was in the post-processual phase from the 1980s onwards that the idea of recreating the past was challenged by the advocates of multivocality (see *PLURALITY AND MULTIVOCALITY*) who argued that there is no single interpretation of the evidence but a social construction in the present highly influenced by the contemporary package carried by the interpreters. During this period—coming about 30 years after the first computer applications in archaeology—three-dimensional (3D) computer graphic visualizations of archaeological sites also appeared and the term virtual archaeology was introduced. The advancement of computational methods and the new technological fetishism reinforced the notion of reconstruction since it was believed that techniques based on automation could achieve accuracy, precision, and objectivity (incidentally the same reasons that governed the wide adoption of photography in archaeology generations earlier).

In the early stages of computer graphics, 3D visualizations of archaeological sites were quite schematic due to the limited computational power and software capabilities, and although the idea of reconstruction was inherent in the processes followed, they were not openly challenged until the advent of photorealism.

Photorealism: a definition

Photorealism appeared in computer graphics in the 1990s when computational power could support an image quality close to or indistinguishable from real life. The term photorealism originated in the United States in the 1960s to

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define a style of painting and sculpture that involved the precise reproduction of a photograph. It is often argued that the predecessors of photorealism can be traced back to Dutch paintings of the seventeenth century and the works of Jan van Eyck, who used optical instruments, such as the camera obscura, to help him accurately render on canvas the scenes in front of him.

Photorealism in digital archaeology—the same way as reconstructions—created a long and heated discussion, especially between 1995 and 2005. The main argument was that due to the ultra-realistic nature and high fidelity of computer graphic visualizations, ideas and meanings that rarely derive from archaeological evidence are conveyed. Although the potential of 3D graphics to communicate or experiment with difficult to understand concepts cannot be denied, there have been numerous attempts to counteract their problematic nature.

Ambiguity and transparency in digital reconstructions

Nonphotorealism, which is a technique for rendering 3D models in more artistic and expressive styles, has been proposed as a way to communicate content and explore interpretations free from photographic realism (Roussou and Dretakis 2003). However, when nonphotorealistic rendering is implemented in an attempt to mimic nonphotographic illustration styles, for example, ink drawing, it takes on many of the tropes of photorealism. Other stylistic methods have been proposed in order to highlight the ambiguity of data and allow users to tell what is based on real evidence, what has been restored based on some form of information, or what is pure artistic license. Examples of these are different levels of transparency, digital annotations with the evidence that led to the reconstruction (e.g., field notes, excavation photographs, scholars' interpretations), and visual degradation of uncertain parts (Eiteljorg 2000).

Technical solutions have also been implemented. For example, the creation of interactive visualizations with parameters that can be changed by the user to demonstrate that more

than one option could be valid in a given context and that any changes in one parameter affects the rest. The construction of multiple 3D models that cover all possible interpretations has been followed by many 3D visualization specialists, although it is not often considered the best option due to the time and effort required for their production. The latter has also been accomplished by the use of procedural modeling which can create models in an automated way based on a series of predetermined rules. Other approaches include the quantification of uncertainty by assigning numeric values to the different elements of the models (Niccolucci and Hermon 2006) or a series of theoretical principles, such as the London and Seville Charters, to ensure that best-practice is followed for the visualization of heritage content.

The London Charter in particular and its elaboration by various scholars suggested the introduction of the term *paradata*—that is, information about the processes that humans use for understanding and interpreting particular data (Baker 2012)—to thoroughly document how data lead to 3D models. The latter, however, is utterly problematic, since it presupposes a somewhat linear process of visualization in which there are clear connections between the evidence and the visual output, without taking into account various factors (e.g., perceptual, physiological, technical) which cannot be predicted, identified, and documented in the course of the modeling process. Any stylistic, technical, or theoretical ways to represent archaeological reasoning cannot capture the complexity of the processes to their full extent and will eventually deceive viewers/users into thinking that any ambiguities are limited to those visualized. Archaeology, however, is much more complicated and its multifaceted nature can fit into neither one nor multiple visuals, databases, and guidelines.

Digital reconstructions: analytical tools and knowledge production

Based on all the above, it becomes apparent that reconstructions—either photorealistic or not—have been considered a problematic practice in digital archaeology, despite the fact that, in

principle, they differ very little from the images that archaeologists are used to producing, including illustrations and photographs. However, the power of photorealism and especially physical realism in digital reconstructions as interpretive mechanisms and vehicles of knowledge production has remained underexplored.

Contrary to photorealism that provides a believable rendering of a scene, physical realism provides a prediction of how the scene would look by taking into account the properties of the objects comprising the scene. In the case, for example, of predictive lighting, software is used to simulate the interaction of light with all surfaces, textures, and colors in a scene in order to produce an image closer to what could have been seen in the past. Considering what has been discussed in the previous sections, it cannot be argued that this method can produce reconstructions of the past. Past lifeways were not formed only by lighting conditions but a series of factors, including visual perception, senses, and the psychological state of the observer, which at the moment cannot be modeled in a digital environment. However, such approaches provide a new way of looking into and thinking about data, going beyond the visual appreciation of images. They can work as analytical tools to simulate variables of the past that could not be taken into account by using any means traditionally used in archaeology.

Lighting simulation (see *SIMULATION MODELING*) and analysis (Papadopoulos and Earl 2014) can be used as a heuristic source that has the potential to enhance understandings and interpretations. For example, in the computer graphic simulation of the “ceramics workshop” at Zominthos, the illumination study and the multiple structural models produced (Papadopoulos and Sakellarakis 2014) challenged the original interpretation of the room as a working space, that is, for making pottery, since the lighting values obtained did not indicate that this could be an environment with enough visual acuity that could provide sufficient light to the potter to work on the wheel. This new interpretation was not a conclusion but a starting point for further discussion and elaboration on the possible uses of space that also led to the re-examination of field notes and other excavation evidence.

Similarly to lighting simulation and analysis, computer graphic 3D reconstructions can work

as analytical tools to investigate other properties and parameters of past environments, providing metric data that can inform the interpretive process. For example, visibility analysis (see *VISIBILITY MODELING*) in 3D spaces has provided a new way of analyzing space (see *SPATIAL ANALYSIS*), as well as discussing and understanding social patterns and socio-symbolic meanings (Paliou 2014). Also, structural analysis can help researchers to build multiple structural models and test hypotheses about the validity of architectural reconstructions and their interpretations. Acoustic modeling and simulation is another tool that has moved archaeological inferences beyond the ocularcentrism of archaeology by considering aural experience and discussing perception and the soundscapes of the past. All these approaches have introduced a novel way of dealing with and enhancing spatial concepts by providing metrics that allow the quantification of interpretations while considering multimodal variables and sensory engagements that would have affected human experience. The latter has been augmented by the advent of virtual reality (see *VIRTUAL REALITY MODELING*) which has developed immersive ways of thinking and understanding spatial relationships, adding the sense of presence in the perception and experience (see *PERCEPTION AND EXPERIENCE*) of past spaces.

Although the power of such tools cannot be denied, it cannot be claimed that by using digital reconstructions and formal methods of analysis the past can be reconstructed. However, computer visualizations are not the last and often unnecessary addition to the presentation of a dataset, and if they continue to be merely seen as products, then the whole attempt to incorporate these in the archaeological process will remain a utopia. The sense of authenticity (see *AUTHENTICITY IN VRM*) that these images carry has long been debated, and alternative ways of approaching this by downgrading, blurring, and coloring visualizations have been proposed. Without neglecting the powerful visual impact they have, we should move a step forward, since we have come to realize that different levels of ambiguity are inherent in the nature of archaeology and consequently in the images produced. This means that since there is no way to avoid the

nature of these images, the stimuli that 3D visualizations provide should be used by thoroughly evaluating and critically approaching hypotheses and results. Computer graphic simulations should be employed as a means of visualizing concepts and ideas, and decision-making processes and interpretations. In such a way, interpretations materialized in the form of 3D visualizations become heuristic sources and working hypotheses in the production of archaeological knowledge, becoming part of a never-ending translation process, augmenting perception and providing stimuli to expand the interpretive vocabulary of the archaeological process.

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Remote Sensing

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The field of remote sensing (see AIRBORNE REMOTE SENSING) in archaeology is growing (Parcak 2008), and has allowed for some of the most exciting discoveries globally since the turn of this century. It covers everything from ground-based systems (magnetometry (see MAGNETOMETRY), resistivity (see ELECTRICAL RESISTIVITY) and ground-penetrating radar (see VISUALIZATION OF GROUND-PENETRATING RADAR DATA)), airborne systems (light detection and ranging (LiDAR) (see AIRBORNE LASER SCANNING AND LIDAR), aerial photographs (see AERIAL PHOTOGRAPHY), unmanned aerial vehicles (UAVs) (see DRONES)) to space-based systems (radar (see SYNTHETIC APERTURE RADAR), satellite imagery (see SATELLITE HYPERSPECTRAL AND MULTISPECTRAL IMAGING)). Archaeologists have debated if remote sensing is now a standard part of archaeology. Given the rapid increase of graduate dissertations and theses, conference papers, grant programs, and academic articles, it appears it is an integral part of archaeology. What is needed presently is a more open discourse on the overall utility of these data, as well as the accompanying ethical issues.

The field of remote sensing has existed for over 100 years, as an early image of Stonehenge, taken in 1908 from a balloon, is considered the first airborne image of an archaeological site. The 1950s saw the growing use of aerial photographs, with early applications of infrared film in the 1960s. Ground-based remote sensing saw major growth during this time as well. The Landsat satellite launched in 1972, and satellite remote sensing articles started to appear by the mid-1980s. Advances in magnetometry and resistivity equipment allowed for more detailed subsurface feature maps in the 1990s, leading to nearly complete ancient town plans. By the late 1990s, archaeologists could access high-resolution satellites

with a 1-m resolution, but at great cost. With the launch of multiple high-resolution satellites ten years later and the availability of Google Earth, in addition to open source processing tools, satellite remote sensing became a low-cost tool for the assessment of ancient landscapes (see ENVIRONMENT AND LANDSCAPE).

Specializing in remote sensing for archaeology often requires specific university graduate-level courses. Archaeologists may take classes as undergraduates in geographic information systems (GIS) (see STATISTICS AND GIS), remote sensing, or landscape archaeology, but will receive advanced training during their graduate work. As it is so landscape- and culture-specific, archaeologists must adapt their approaches and tools over several seasons. GIS and remote sensing software packages are readily available, and with open source GIS tools like the geographic resources analysis support system (GRASS), cost is no longer an issue for researchers. It is not possible to specialize in all forms of remote sensing, so archaeologists tend to choose between ground- and space-based tools. Also, surveyors may join an excavation without extensive previous archaeological experience.

Archaeologists have made major discoveries using remote sensing this century. At the site of Angkor Wat in Cambodia (Evans et al. 2013), archaeologists have used LiDAR, a laser sensor system flown on airplanes, helicopters, or unmanned aerial vehicles (UAVs), to map most of the temple complexes, many of which are beneath dense rainforest. In Belize (Chase et al. 2012), LiDAR has helped archaeologists map thousands of previously unknown Maya sites and features. High-resolution satellites, combined with LiDAR and magnetometry, have revealed a potential amphitheater, roads, and warehouses at the site of Portus (near Rome), Italy (Keay, Parcak, and Strutt 2014). At multiple sites in Egypt, magnetometers have revealed the outlines of ancient cities (Rosenow 2010). In each case, the importance of ground truthing the results must be emphasized. While a feature may be clear from space or airborne imagery,

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archaeologists must confirm it with survey or excavation. Finally, satellites have helped archaeologists to map hundreds of thousands of looting pits across the Middle East (Parcak et al. 2016).

Now it is possible to ask new questions about ancient sites using remote sensing. Archaeologists can examine ancient human–environment interactions in far greater detail when they know the locations of defunct river beds or ancient sites partly covered by modern towns. They can better plan grant applications with Google Earth, which allows for exploration of sites prior to visiting them on the ground. Regional approaches will vary widely, as LiDAR is not permitted in some Middle Eastern countries, while satellite imagery will not work in much of Central America or Southeast Asia due to vegetation coverage. There is no “one size fits all” approach, as landscapes, seasonality, country permits, access, and cost may affect the types of remote sensing any project may do.

New advances in the resolution of satellite data (now 0.3 m) and its spectral ranges, and the ease of using GIS (with countless online tutorials) are allowing for greater experimentation and the pushing of boundaries. Crowdsourcing efforts like GlobalXplorer (www.globalxplorer.org) are allowing thousands of members of the public to examine satellite imagery and contribute to heritage mapping efforts. Drones now can carry LiDAR along with hyperspectral cameras and multispectral sensors, making it possible to image nearly anywhere in the world at great resolution.

How, then, should we protect and store all these newly collected site data? These and many other ethical issues remain to be debated. The future of remote sensing for archaeology is exciting, but should be approached with caution.

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Scanning Probe Microscopy

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Scanning probe microscopes (SPMs) measure surface properties such as roughness. SPMs include atomic force microscopes (AFMs) and scanning tunneling microscopes (STMs). The development of the SPM or the AFM began with the invention of the scanning tunneling microscope (STM) in 1982 by G. Binnig and H. Rohrer. Initially, the first SPMs were used to measure three-dimensional surface topography. The common trait of many SPMs is that the measurements are obtained with a sharp probe or tip (commonly shaped like a pointed triangle) mounted at the end of a cantilever. The first instruments to show arrangements of atoms on flat surfaces were STMs, but the application of the STM to archaeological samples is limited.

To operate a SPM, the sharp tip is mounted on one end of a cantilever and moved in three directions including the rastering movement in both x and y planes and moved in the vertical direction (up and down in elevation or z plane) very close to the surface to be analyzed. Piezoelectric crystals mounted at the cantilever's other end move the tip precisely in the x and y planes because the crystals can accurately change their shape in response to a computer-controlled electric field. The crystals unerringly raster the tip (in the x plane) in a line from one edge of the sample area of interest to the opposite edge, and then the tip shifts position slightly (in the y plane) to begin another passage over the sample in the x plane (in the opposite direction). These rastering movements (in the x and y planes) are completed again over and over until the tip has traveled across the entire area of interest. The position of the tip in the z plane (up and down) is influenced by van der Waals forces (and other small-scale atomic forces), so the same clearance between the tip and the sample surface

is maintained despite changes in the elevation of the sample surface topography.

Needle movement in many AFMs is precisely plotted by focusing a laser beam on the top of the cantilever. This beam is reflected onto a light-sensitive screen so any movement of the cantilever and tip in all three planes (x , y , and z) is digitally recorded while rastering the sample surface. Computer software can construct a three-dimensional map of the surface by careful correlation of the plotted position during rastering (x and y) related to changes in the z (elevation of surface) position.

Different contact modes in AFM

Many AFMs can be placed into different tip contact modes during operation. During contact mode, the tip of the cantilever gently touches the sample surface as it rasters the area of interest. The topography of the sample causes the tip to move and deflect the cantilever. As the tip contacts the surface and moves along it while rastering, strong repulsive forces (between atoms) cause the cantilever to deflect away from the surface only slightly. But subsequent tip contact with the sample will reduce resolution as the tip is dulled. In non-contact mode, the cantilever tip vibrates (or oscillates) just above the sample surface while rastering. Using a rapid response feedback loop, the oscillation amplitude decreases as the tip approaches the sample. Only rarely would tip contact occur in this mode. In tapping mode, the cantilever oscillates near the surface of the sample, but at higher amplitude of oscillation than in non-contact mode. With a greater deflection signal (the indicator that the surface is near), better topographic control is achieved so a rougher sample surface can be mapped than with non-contact mode. Some manufacturers, such as Park Systems (2016), have introduced a unique non-contact technique that allows tip and sample preservation as well as a very small tip-to-sample distance to provide very good resolution. A vibrating cantilever is controlled in

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part by both static electric repulsive forces and the attractive force between atoms of the sample. These forces include the equal sharing of electrons for non-polar molecules, the unequal sharing of electrons in polar molecules, and the transfer of electrons in ionic molecules. Depending on the types of bonds existing in the sample atoms, the complex forces at the sample surface interact with the forces of the atoms of the cantilever needle to establish a distance from the sample surface at equilibrium. As the vibrating tip distance to the surface is shortened due to an increasing elevation of the sample surface, the repulsive forces between tip and surface increase, and the increase in force results in an increase in distance. Using vibration amplitude adjusted to maintain a clearance of a few nanometers from the sample surface, any changes in sample elevation are easily recorded as changes in the cantilever vibration frequency because the repulsive atomic forces change the frequency of cantilever vibration. These changes in frequency vibration are digitally transformed into two-dimensional diagrams of surface roughness or three-dimensional maps of the surface. The tip rarely touches the surface of the sample with this system because the high frequency vibration of the cantilever allows very small tip movements to detect surface elevation changes.

Microwear studies of replica and archaeological tools using AFM

Early AFM research was carried out by Kimball, Kimball, and Allen (1995) using the digital software built into the AFM to create three-dimensional top views, surface plots, and cross-section profiles. The differences observed by AFM between surfaces of hafted experimental backed bladelets used to work wood, antler, dry hide and meat for 1 hour each were compared with unworked bladelets from the same nodule. The resulting differences in polish between bladelets as a result of working different materials could be discerned by using incident-light microscopy and hand lenses up to 200 $\times$ magnification. This method was based in part on the early work of Semenov (1964) in Russia and later Keeley (1977) using incident-light microscopy in the West. The AFM was also used to characterize the use of these bladelets using

polish features, which correlated well with the postulated use of bladelets determined using the Keeley method. These results are quite impressive considering that the area that could be effectively scanned (in 1995) was very small, roughly 15 $\times$ 15 micrometers (Kimball et al. 1995).

The software output commonly produced by AFMs such as the Veeco Icon AFM (Faulks et al. 2011) includes not only three-dimensional topographic images of a sample surface, but statistical evaluations of these surface characteristics defined as roughness, skewness, and kurtosis. Roughness is usually quantified as the average of the differences in elevation between the lowest areas of a sample compared with the highest adjacent areas of a sample. If these differences were very great for a sample area, then the sample would have a larger roughness value. Skewness is a determination of the sample symmetry, so that a sample surface having only slightly raised plateaus would have smaller skewness values, but another surface comprising steep peaks and low valleys would have greater skewness values. Kurtosis pertains to the shape of a distribution curve of the roughness values of a sample. The kurtosis for a sample area that approached that of a normal uniform bell curve would be higher than that of a sample area that had greater disparity in the distribution of roughness values.

Experimental microwear pattern analysis derived from experimental tools used to work different materials was compared with the results of analysis of features of microwear polish on Middle Paleolithic (Mousterian) flint tools from Myshtylagty Lagat (Weasel Cave), Russia (Faulks et al. 2011). The microwear on experimental tools was produced by contact with meat, fresh hide, dry hide, bone, wood, and hafting. The wear surfaces of both experimental and Mousterian tools were analyzed using the qualitative approach by Keeley (1977). The wear patterns of experimental tools used for working different materials were described and compared with wear patterns on tool artifacts from the site. Matching patterns on experimental tools were used to postulate the use of tool artifacts. The wear surfaces of both experimental and Mousterian tools at Weasel Cave were also analyzed by the quantitative system of AFM, which determined that meat and dry hide polishes are least developed with smaller changes in roughness (in nm) while

bone and wood polishes are more developed and have larger changes in roughness (in nm). These quantitative (rather than qualitative) values, especially skewness and kurtosis, could distinguish polishes produced by cutting meat versus cutting dry hide, a difference difficult to verify by simply examining roughness or morphology by the Keeley Method (Faulks et al. 2011, 314). Scans of 50×50 micrometers were possible in order to produce three-dimensional surface maps.

Archaeological pottery analyzed using AFM

Using AFM, a non-fired slip (material applied to a pottery surface for the purpose of decoration) was identified covering the ceramic matrix material composed of hydrated calcite and volcanic stone fragments of Zaghe (Iran) ceramics (5100 BCE). This non-fired silica-rich slush could be one of the oldest slips discovered which continuously covers the ceramic matrix. Grain boundaries and the defects due to processes known as sintering by partial smelting were detected by AFM because boundary decomposition and rebuilding processes are readily apparent (Emani et al. 2016, 18).

Laser scanning confocal microscopy is similar to AFM

Laser scanning confocal microscopy is a surface analysis technique very similar to AFM that has also been employed to characterize archaeological lithic materials (Evans and Donahue 2008). A LSCM uses a laser to reflect light only in precise focal planes across the specimen. The laser light reflected away from the focal plane is removed. The focus plane is motorized to move in discrete steps. An image is taken at each focal plane and these horizontal “slices” of the sample are processed so a three-dimensional image of the sample can be constructed. The resolution in each focal plane is 0.12 micrometers and as much as 10 nanometers in the vertical resolution. The LSCM produced 3D images measuring 96×128 micrometers of flint surfaces used to work antler, wood, fresh hide, dry hide, and greasy hide. These images could be differentiated by their method of

creation using standard roughness measurements employed for characterizing surface roughness in engineering. No needle is used in this system, so no contact occurs with the surface (Evans and Donahue 2008).

Using LSCM, the importance of the effect of different workloads on wear development on experimental stone tool surfaces was demonstrated (Stemp, Morozov, and Key 2015). Previous studies tended to relate duration and intensity of use to increased wear effects. Basalt flakes knapped from raw material collected from Olduvai Gorge, Tanzania, were used to cut oak branches with the same number of strokes but with loading levels applied in increments of 150 grams to 4.5 kilograms. Surface wear data were analyzed using area-scale fractal complexity, relative area analysis, and mean square ratios, which indicated that only above roughly 100 grams could a consistent discrimination of worn flake surfaces by the applied workload be made (Stemp et al. 2015).

A good level of agreement was obtained for the assignment of the tool used to produce wear on Monterey chert utilizing either the conventional Keeley method or the LSCM (Stevens Harro, and Hicklin 2010). Experimental tool wear of replica edges of Monterey chert flakes produced by cutting antler, wood, soft plants, dry hide, and meat was analyzed by both these methods, along with unused replica tool edges. The wear edges (and unused interior edges) of Monterey chert tools from CA-SBA-246, an Early Holocene (ca. 9200–8800 BP) archaeological site on the central California coast, were also analyzed with the Keeley method and with the LSCM. Of course, unlike the experimental chert tools, the material that created the wear on chert tools in the archaeological site was unknown. Therefore the type of tool presumed to create wear was assigned based on the agreement between quantitative machine-based LSCM data and qualitative human analysis using the Keeley method (Stevens et al. 2010).

Future directions

While the claims of researchers concerning resolution or the size of the area of a sample that can

be analyzed by a particular technique are correct when published, it should be remembered that these numbers are for specific types of samples, specific research goals, and equipment current at the time of publication. The types of technology, resolution, and software for AFM, LSCM, and other tools used in surface measurement are always improving. New techniques are constantly evolving, so researchers should choose equipment that best matches their scientific goals following a survey of available surface measurement devices and associated software options.

SEE ALSO: Micromorphology; Mobility and Strontium Isotopes; Nanoarchaeology

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Semantic Web and Ontologies

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The Semantic Web and ontologies can help archaeologists combine and share data, making the data more open and useful. Archaeologists create diverse types of data, using a wide variety of technologies and methodologies. Like all research domains, archaeological data are increasingly digital. In addition, they are often the result of nonrepeatable interventions, either because field methods (such as excavation) result in destruction of the physical resource, or because sampling strategies are invasive and must therefore be limited. These factors combine to make archaeological data nonreproducible in many instances, but also fragile due to the inherent issues of digital obsolescence. Digital archaeological data are therefore often considered primary data, and must be preserved and made available for reuse by future researchers. This obligation has made archaeology an early adopter of open data sharing and efforts to make data persistently available. Since the 1990s, we have seen the advent of digital data archives and repositories with a specialist understanding of how to work with the diverse data produced by archaeologists. The creation of data that are openly and persistently available from disparate sources has also inspired efforts to bring archaeological resources together and make them interoperable. This allows functionality such as federated cross-search of different datasets, and the mapping of heterogeneous data to authoritative structures, in order to build a single data source and facilitate the creation of new knowledge.

Tim Berners-Lee, the creator of the World Wide Web, coined the term Semantic Web. The World Wide Web is of course highly successful, but its structure is based on a “Web of documents” comprised of pages linked together, but without a way to make connections between the

data held within those pages. In addition, Web sites are increasingly powered by databases, but hold data in ways that do not allow connections to be made. Data served in this way are usually referred to as being “siloed.” In 2001, Berners-Lee, James Hendler, and Ora Lassila published their vision for the development of a “Semantic Web” conceptual framework to move from a “Web of documents” to a “Web of data” by creating data in a format that is machine-readable (Berners-Lee, Hendler, and Lassila 2001). In order to do this, data needed to be structured in a new way, so the Semantic Web is associated with a structure called graph data. Graph data are organized into a three-part relationship of subject, predicate, and object, also referred to as a triple. Thus, graph databases are often referred to as triplestores. The data held within a Semantic Web-based triplestore are also commonly known as Linked Data, or when made openly available, Linked Open Data.

When using data, especially shared data, metadata becomes very important. Metadata describes what the data are. For example, if an archaeologist has a spreadsheet with faunal measurement data from an excavation, the spreadsheet might have several columns with numbers in each column. Without the heading at the top of each column stating what the numbers are (e.g., femur length), the numbers have no meaning. The numbers are the data, but the column heading is the metadata, providing its structure and relationships. With Linked Data, that metadata structure is typically created by mapping the data to a controlled vocabulary (which is similar to choosing predefined terms in a relational database), a thesaurus (where the terms also have a hierarchical relationship; which is similar to choosing terms and subterms in a relational database), or an ontology (a more complex way of not just organizing terms but also defining entities, properties, and their interrelationships). Formal definitions of what constitutes an ontology differ, and this is further complicated by the frequent use of the word “ontology” as a general term for describing any of the above mapping schemas for graph data.

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Whatever the level of complexity chosen for the mapping structure, this approach requires qualitative agreement that concepts from disparate data sources are acceptably similar. For example, an archaeologist working on one project maps the name of the person who created a field drawing to the concept “recorded by” from an “ontology” describing archaeological fieldwork. When an archaeologist from another project sees this concept within the field recording “ontology” and determines that the definition (also known as a scope note) for the name of the person responsible for field recording matches their own (along with any other parts of the schema deemed appropriate), then the data for the two different projects become “interoperable.” Interoperable data are much more powerful and flexible, as they can be combined and compared more quickly and easily, and allow for new and different interpretations. This concept of interoperability is at the heart of the Semantic Web, but the frameworks and technologies still require archaeologists to agree on the meanings of terms and concepts. This is not always possible or advisable, however, and archaeologists must think carefully and critically about how they map their data, and determine whether the benefits of interoperability outweigh potentially diminishing the diversity or richness of their data and any subsequent research derived from it.

Graph data mapped to an ontology or other type of schema are typically expressed using the Resource Description Framework (RDF). RDF is a data modeling framework for defining the structure and relationships within a data resource. The different types of data to be modeled are typically referred to as classes, and the relationships between the classes are called properties. Classes are things to be queried, assessed, quantified, or manipulated. In archaeology, this might include artifacts, places, soil types, features, or contexts. Properties describe the relationships between resources, like “is fashioned from,” “is in the style of,” “is nearby,” “is parallel to,” “cuts,” or “is cut by,” and so on. The classes and properties of resources are asserted by something called a statement, and a statement in RDF is called an RDF triple.

An RDF triple is two classes joined by a property, and expressed as a “subject, predicate, object” grouping. The RDF triple is the basic

building block of the Semantic Web, and all Semantic Web data can be organized within this simple format. Taking an example from data held in the archive *Stone in Archaeology: Towards a Digital Resource* (University of Southampton 2005), archaeological information expressed as an RDF statement might look like:

Ashford Black Marble *was mined at* Arrock Mine.

In this statement, the subject is “Ashford Black Marble,” the predicate is “was mined at,” and the object is “Arrock Mine.”

RDF can be written in a variety of ways, known as serializations. One of the simplest is called N3 notation. In N3, the above statement could be written thus:

```
@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
@prefix sia: <http://dataservice.org/stoneinarchaeology/ontology/>
<sia:Ashford Black Marble> <sia:was-mined-at>
<sia:Arrock Mine>
```

The first line defines the location of the RDF syntax, so any machine processing the data will understand that it is RDF; the second line defines the location of the (entirely fictitious) *Stone in Archaeology* ontology, which allows any machine processing the data to recognize the terms within the ontology and understand the relationships between them. Rather than include the entire Web address for each piece of information, namespace abbreviations are used to create a shorthand which is more human readable: in this case, “rdf” for RDF and “sia” for Stone in Archaeology. Each piece of the triple can then be written using the appropriate prefix followed by the desired value. The third line shows the triple statement “Ashford Black Marble was mined at Arrock Mine.” More information can be easily added:

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@prefix rdf: <http://www.w3.org/1999/02/22-rdf-syntax-ns#>
@prefix sia: <http://dataservice.org/stoneinarchaeology/ontology/>
<sia:Ashford-Black-Marble> <sia:was-mined-at>
<sia:Arrock-Mine>
```



```

<sia:Ashford-Black-Marble> <sia:was-mined-at>
  <sia:Rookery-Mine>

<sia:Rookery-Mine> <sia:is-a-quarry-near>
  <sia:Bakewell>
<sia:Arrock-Mine> <sia:is-a-quarry-near>
  <sia:Bakewell>

```

This group of statements tells us that Ashford Black Marble was mined at both Arrock and Rookery Mines, and that both mines are in quarries near Bakewell. Note that Arrock Mine and Rookery Mine appear as both subjects and objects. This shows the essential way data link together in RDF. Groups of linked triples come together to form what is known as a “graph.” As graphs are built, new relationships can be inferred. In the example above, it can be inferred that Ashford Black Marble can be found near Bakewell, even though it is not stated explicitly. Inference is one of the key advantages of using Semantic Web frameworks and technologies. In addition to interoperability and inference, data held in RDF and graph format can branch in any direction to form new relationships whenever new data are added, all of which is difficult in traditional relational data structures.

CIDOC CRM is the most commonly used ontology in the cultural heritage domain. It is a formalized set of terms and relationships between those terms, specific to cultural heritage data, and became an official ISO standard in 2006. CIDOC CRM was designed for cultural heritage generally and has become a basis for ontological modeling in the archaeological domain, but does not describe archaeology specifically. One of the first efforts to create an archaeological “extension” of the CIDOC CRM was carried out by Historic England in the United Kingdom. Created in partnership with the University of South Wales, the “CRM-EH” retains coarse-grained interoperability with the CIDOC CRM, and therefore any other data within the cultural heritage sector also mapped to the CIDOC CRM (University of South Wales 2017). The CIDOC CRM Special Interest Group is now collaborating on development of a series of domain-specific extensions, including several relevant for archaeology. These include CRMsci for scientific observation, CRMgeo for spatiotemporal modeling,

CRMba for archaeological buildings, CRMtex for ancient texts, and CRMarchaeo for archaeological excavation. Work on development of these extensions is ongoing, along with discussions about further extensions for other subdomains within archaeology.

A variety of archaeological data resources already make use of “ontologies” and Semantic Web principles and technologies. One of the best examples is Pelagios Commons (<http://commons.pelagios.org/>). Pelagios Commons is a research community working to develop infrastructures for the humanities based on ancient places. This includes the Recogito (<http://recogito.pelagios.org/>) annotation platform where researchers can manage and share their work with other resources connected to an ancient place, and the Peripleo (<http://pelagios.org/peripleo/map>) search service, which allows researchers to undertake map-based searches across a wide variety of interoperable datasets associated with ancient places. Pelagios is also an example of best practice because it uses Linked Open Data from many outside sources—making them interoperable and searchable through a sophisticated Web interface, while also making the data they hold freely available to other Semantic Web-based applications via an application programming interface (API).

There are other online archaeological resources using and/or creating Linked Open Data, but because it is meant to be machine readable, it may not be as obvious to users. Some examples include the Portable Antiquities Scheme (<https://finds.org.uk/>), Open Context (<https://opencontext.org/>), the Alexandria Archive Institute (<https://alexandriaarchive.org/>), the Archaeology Data Service (<http://archaeologydataservice.ac.uk/>), Fasti Online (<http://www.fastionline.org/>), and ARIADNE (<http://portal.ariadne-infrastructure.eu/>). New approaches are also being explored, such as PeriodO (<http://perio.do/>). PeriodO is an authoritative gazetteer using assertion to define archaeological time periods. It does this by aggregating definitions derived from authoritative sources, rather than using global concepts found in traditional top-down “ontologies.” This addresses the problem of “when” always being tied to “where” in archaeology (e.g., the Bronze Age in Sicily may not refer to the

same chronological dates as the Bronze Age in Yorkshire).

The use of the Semantic Web and ontologies within the archaeological domain will continue to adapt, change, and expand, but this is predicated on Linked Open Data resources being persistently available. Future work is likely to include more seamless integration into many aspects of archaeological workflows, such as digital data capture in the field and post-excavation analysis. User interfaces that take greater advantage of the new types of federated queries and inference afforded by graph data and Semantic Web technologies will be created and tested. Tools allowing archaeologists (who are not specialists in digital methods) to more easily map their data and convert it to Linked Data will be improved.

SEE ALSO: Computer Applications in Archaeology; Databases in Archaeology; Digital Heritage; Information Modeling

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FURTHER READINGS

Simulation Modeling

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Simulation modeling is a technique that uses computational experiments for deriving statements about a system. It is typically applied when real experiments would prove unviable (too expensive/dangerous) or the investigated system is a hypothesis in itself. The latter case is reflected in a large body of literature dealing with *artificial societies*, most prominently the Artificial Anasazi model (Dean et al. 2000) which investigates settlement dynamics in the Long House Valley (Arizona, US) between 800 and 1350 CE, establishing what rules led to simulation outcomes that closely resemble the archaeological record. Other examples extending from modeling social change (Doran et al. 1994) over the dissemination of culture (Axelrod 1997) clearly illustrate the versatility of this method beyond its use in archaeology.

Modeling process

When seen as a process, simulation modeling is initially concerned with the finding of a mathematical description of a real or assumed system (*modeling*). The resulting *model* represents an abstraction and formalization of the system; it leaves irrelevant details out and captures its essence mathematically, in the form of explicit rules and parameters that can be translated into a computer program in a next step (*implementation*). In a final step, the program is run repeatedly using different settings for its input parameters (*simulation experiments*). The outputs of the program are then analyzed and used to infer statements about the system. Furthermore, simulation results may be used in an iterative fashion to adjust the system's definition itself, thus establishing a spiral process when applied repeatedly.

In parallel to the aforementioned steps, there are a set of activities which aim at improving the quality of the overall process: *Verification* ensures that the model is implemented correctly ("Is the model developed right?"), while *validation* tries to ascertain that what goes into the model ultimately serves the intended research question ("Is the right model developed?"). A further work step lies in the choice of parameter settings. If the range of values for a parameter is known, one still needs to pick out sensible settings for each experiment (*parameterization*). If the value of a parameter is unknown, one may still be able to determine it by *calibration*: Initially, a value range for an unknown parameter is estimated, either through expert knowledge or simply by guessing. In a next step, the simulation is run repeatedly using values from that range, until it has been sufficiently covered. Parameter values for which the simulation produces outputs in agreement with a predefined ground truth (typically the archaeological record) are then deemed possible values for the missing parameter. All of the assumptions and decisions taken during the modeling process should furthermore enter a detailed *documentation* (see, for example, the ODD (overview, design concepts, and details) protocol by Grimm et al. 2010 for a guideline).

Types of models

Depending on formalization, models are characterized as being either *discrete* or *continuous*. In archaeological simulation, this mostly refers to the formalization of space and time: *Discrete-time* models treat time as fixed intervals (seconds, months, or years), while *continuous-time* models work at an arbitrary resolution. Likewise, *discrete-space* models use a grid, while *continuous-space* models work with arbitrary geometry. A further characterization can be done by regarding the outcome of the simulation experiments: *Deterministic models* yield the same results when executed repeatedly, while *stochastic models* give different results since they depend

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on randomness. For the latter, one thus needs to conduct more *simulation runs* for each experiment, in order to arrive at statistically significant outcomes.

When building a model, researchers have to initially choose between two alternative ways of decomposing the modeled system: It may either be split into its basic constituents (*microscopic model*, bottom-up approach) or be described on the highest level, naming parts that are interacting (*macroscopic model*, top-down approach). In each of these two classes there exist a variety of *modeling paradigms*—readily available patterns which are used as a blueprint, each one entailing a specific perspective on the modeled system.

The simplest microscopic paradigm is given by *cellular automata* (CAs), which are both time-discrete and space-discrete: Space is partitioned into a grid in which each cell has a state (e.g., live, dead). In each time step, the CA executes a set of rules for every cell, in order to determine what state it should take in the next step. A famous example of that is given by the update rules for Conway’s *Game of Life* (Gardner 1970), which take the state of a cell’s eight grid neighbors into account. Every live cell having

two or three live neighbors stays live (*survivals*). A live cell having four or more live neighbors dies of overpopulation, and a cell with less than two live neighbors dies from underpopulation (*deaths*). Each dead cell adjacent to exactly three live cells becomes live, as if by reproduction (*births*). Despite having no explicit definition of movement within the rules, Conway’s CA is able to produce patterns that float through the grid, oscillate (see Figure 1a), or stay stable. It is an example of *emergence*—simple behavior on a micro level that results in complex behavior on a macro level. Another example from the social sciences lies in Schelling’s model of segregation (Schelling 1969), which is outlined in Figure 1b: In an initial step, each cell is attributed one of three colours (e.g., white for unoccupied, blue or green for occupied). The update rules state that an occupied cell “moves” to an unoccupied location if surrounded by less than a certain percentage of the same color (note: technically, moving a cell is done by swapping colours). After a number of steps, segregation starts to occur (see right in Figure 1b). The simulation ultimately stabilizes when all cells are surrounded by cells of their own kind.

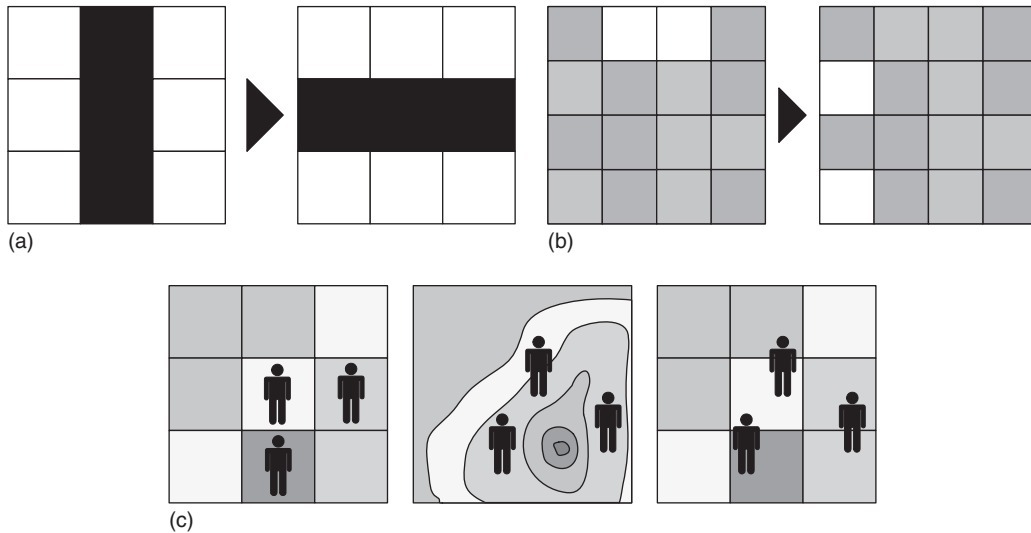


Figure 1 (a) “Blinker” pattern in Conway’s Game of Life. (Left) Initial distribution of live cells depicted in black; (right) distribution after one time step. (b) Schelling’s segregation model. (Left) Initial population distribution; (right) segregation occurring after a number of time steps. (c) Spatial discretization in agent-based modeling (ABM). (Left) Discrete-space ABM; (middle) continuous-space ABM; (right) mixture with discrete-space environment and continuous-space agent movement.

Extending CAs by moving entities (*agents*) yields the paradigm that is most commonly used in archaeology: *agent-based modeling* (ABM; see left in Figure 1c). Every agent has a state and a number of update rules which are applied in every time step. Such rules look just like CA rules, only they allow for additional interactions (agent-agent; agent-cell, e.g., “If the cell I am standing on is yellow and there is at least one neighboring agent, change position to a cell which is not blue and has no agent on it”). The CA forms the *environment* for all agents, which can act either on themselves (cell-cell, as in classical CAs) or on agents in their vicinity (cell-agent).

The example given left in Figure 1c shows a discrete-space ABM: Agent positions are constrained to cell centers and agent movement really means “hopping” between these. The previously mentioned Artificial Anasazi model (Dean et al. 2000) is an example of such a purely discrete ABM: In every year, the CA calculates the yield as a state variable for each arable cell. Households (agents) are situated in the center of a specific cell (the “settlement”). They have a designated farming spot (different cell) which they “harvest” by (1) deducting a certain amount from that cell’s “yield” state variable and (2) adding that to its own “harvest” state variable. In case the harvest plus any food left in a household’s “store” (also a state variable) is insufficient for the coming year, the household tries to find a new settlement and farming spot, both at the center of a cell. The Anasazi model is a representative of the wider class of models referred to as Sugarscape (Epstein and Axtell 1996), in which agents collect a desirable substance (*sugar*) that has been deposited on a grid. As with CAs, a typical characteristic of these approaches lies in the emergence of complex behavior (e.g., wealth distribution according to power-law in the original Sugarscape model).

There are also continuous-space ABMs that use *maps* instead of CAs as environment (see middle part of Figure 1c). They are typically embedded in—or import data from—a *geographical information system* (GIS) which holds the spatial features through which agents can move freely. These features tend not to have update rules as cells of a CA would; instead, the environment behaves as a passive part of such models, being used for queries (e.g., “If elevation at current point is above sea level, move forward”).

As a third and nowadays most commonly used option, ABMs can be implemented as a mixture involving a discrete environment (i.e., a CA) through which agents can move continuously (see right in Figure 1c). The main advantage over discrete-space CAs lies in the fact that small-scale agent movements can be simulated with greater accuracy (pedestrian dynamics, crowd simulation) and appeal (visualization).

There are scarcely any approaches in archaeological simulation using modeling paradigms other than CA and ABMs, even though some would be quite similar in scope. For example, *discrete-event simulation* (DES) can be used to simulate long-running processes on a micro-level. It is a paradigm that models only state changes (i.e., beginning and ending of an activity), which allows the simulation to skip the time in between. A further paradigm called *system dynamics* (SD) is beginning to be applied for macro-level aspects such as economical flows and population development: It models *stocks* holding quantities and *flows* (changes in quantity over time) between these. In contrast to the paradigms presented earlier, SD is a continuous-time approach, that is, flows theoretically happen in infinitesimally small time steps (*dt*). However, computers will use discrete (but very small) time steps in practice.

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Spatial Analysis

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Spatial analysis refers to the study of spatial distributions of archaeological and related phenomena. The identification and understanding of spatial patterning has been inherent to archaeology since provenances of artifacts were first recorded in the nineteenth century. Early inquiries were a matter of subjective impression until spatial analysis emerged as a subdiscipline in the 1970s. It has its genesis in the quantitative geography movement of the 1950s–1960s whose methods were later adopted for archaeological problems (e.g., Hodder and Orton 1976). Initially, nearly all spatial analyses rested within the province of mathematics and statistics, with an important side-trajectory that included incipient computer graphics which permitted ancient mapping and visualization of distributions (e.g., the SYMAP program). This duality of quantitative and visual approaches continues today, although in much evolved forms. A second early division was between analyses that focused on archaeological distributions *within sites* versus those that occurred at a regional scale or *between sites*. This division characterizes most applications today, although wider domains are now included, ranging from use-wear pattern distributions on artifacts, often linked with image or residue analysis, to continental or global scales that examine group movements of cultures or cultural elements through time and space. Regional analyses typically examine relationships between settlements (or other areas of human activity) and the social or physical environment, or the nature of how they are located relative to each other, and this division reflects yet another dichotomy fundamental to spatial analysis. First-order effects occur when variations in environment (e.g., soil quality) influence archaeological distributions, while second-order effects occur when interactions between the elements themselves impact their

distributions. Both processes mean that chances of occurrence vary over space, making them “nonstationary” or “inhomogeneous,” which can lead to uniformity or clustering of distributions.

Early work through the 1980s was primarily empirical and statistical. Intra-site analyses examined distributional differences in artifact or faunal assemblages and second-order effects that formed “activity areas” and co-occurrences of tool types, referred to as “tool kits” (summarized in Hietala 1984). Despite issues stemming from boundary problems, nearest-neighbor analyses provided useful indices of relative dispersion or clustering of artifact classes. Local density analysis, Hodder and Okell’s A, and multi-response permutation procedures went a step further, the first by considering all distances within a defined radius of each object, and the remainder by assessing distances between *all* artifacts within analyzed classes to determine spatial association or segregation without boundary issues. “Pure location clustering” referred to a method that identified natural clusters of artifacts, presumed to reflect areas of activity, through the k-means algorithm applied to two-dimensional spatial coordinates. “Unconstrained clustering” identified clusters based on artifact types that consistently occur together within a site, so-named because clusters were unconstrained by shape, size, or density.

At the regional level, a variety of procedures were developed to ascertain environmental and other variables relevant to archaeological site locations, or first-order effects. *Site catchment analysis* (SCA) focused on environmental circumstances within site neighborhoods or “catchments” defined by an exploitation radius of a few kilometers. Differences in resources were argued to influence variations in population, political power, and the like. Other approaches focused on location associations between sites and environment using chi-square goodness-of-fit tests for nominal-level variables such as soil types. For quantitative variables (e.g., distance to water, elevation), measurements made at site locations were statistically compared against measurements at random samples of

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nonsites (locations of site-absence); differences implied location tendencies in site placement. Second-order effects were investigated largely through quadrat count methods that assessed clustering or dispersion through comparisons against expectations of a Poisson distribution, but which were highly influenced by scale changes. Modeling utilized trend-surface analyses, which generalized trends (e.g., dates of initial colonization or of the Maya Collapse) across broad regions based on low-order polynomial interpolation functions (Hodder and Orton 1976).

By the 1990s the adoption of GIS technology had a tremendous impact because it increased by orders of magnitude the volume of spatial data that could easily be handled, especially at the regional level. It also encouraged a change in the direction of spatial analysis, which began to lean heavily toward visualization (and away from quantification) because simple overlays of archaeological distributions facilitated recognition of second-order spatial relationships, or they could be overlaid atop environmental distributions (e.g., soils, hydrology) to facilitate discovery of first-order effects.

The initial application of GIS to archaeological spatial distributions was primarily for archaeological location modeling, often referred to as “predictive” modeling (see PREDICTIVE MODELING) (see papers in Wescott and Brandon 2000). This application was largely driven by cultural resource management needs where environmental differences on multiple variables reflected by samples of sites and nonsites in a region could be subjected to multivariate analyses using discriminant functions or logistic regression. GIS map algebra tools permitted mapping of the resultant functions over entire regions to yield probability surfaces for archaeological presence, ideal for management purposes. Other approaches employed Boolean models that mapped the intersection of relevant levels of important variables to indicate likely regions of archaeological presence.

Archaeologists soon began to utilize the potential of other features in the GIS toolbox for addressing various spatial questions (Conolly and Lake 2006). Pathway analysis goes beyond consideration of simple linear distances between places by computing the difficulty or cost of movement through landscapes in terms of “effort” expended

(e.g., calories or travel time), variations in terrain, and impediments to travel (water bodies, vegetation cover). Algorithms ascertained routes that minimized travel costs between predefined points. Resultant nonlinear distances improved the accuracy of proximity variables in settlement location analyses; other studies compared least-cost pathways against known travel routes or settlement distributions.

GIS offered a variety of approaches for spatial allocation, the assignment of spaces to objects, which is ideal for investigating concepts of territoriality. Buffering tools defined areas based on linear distances to delineate circular catchments around settlements, making SCA easy to implement. Tessellations such as Thiessen polygons permitted variations in territory definition. An improvement utilized “weighted Thiessen polygons” where settlement territories were sized according to a quantitative index, such as population. These methods were based on simple geometries and an assumption of an isotropic plane with uniform access or movement costs. Greater realism was achieved by factoring in costs of movement around settlements by considering terrain, vegetation cover, and barriers such as rivers. Results yielded landscape-adjusted territories that were highly variable in shape and size.

Intervisibility studies identified locations visible from a site (or the converse, whether a site was visible from a locus); the resultant mapping is termed a *viewshed* (see VIEWSHED ANALYSIS) (a binary result coded unity where visibility occurs; zero otherwise). A *cumulative* viewshed considers several binary viewsheds and expresses the result as a count or proportion of the number of targets visible from a locus. If targets are burial grounds combined viewsheds have been argued to define a “sacred” space; other approaches have examined whether specific landscape features (e.g., a prominent mountain) were commonly seen. Such studies led to the idea that viewsheds enable study of ancient perception. Others saw viewsheds as only another landscape variable in location analyses by comparing relative sizes of viewshed or whether rival settlements were visible as a defensive consideration. Viewsheds may define social territories: their boundaries have been shown to coincide with regions defined independently by Thiessen polygons, for example.

Since the turn of the millennium, three developments have influenced the direction of spatial analysis: (1) powerful computing became available, even on desktops; (2) a flood of digital information took place as the Internet matured and as spatial technologies developed; and (3) development of a wider climate of easy-to-use and open-access software. Two approaches to spatial problems emerged. One was model-based and grounded in renewed interest in simulation caused in part by open-source software offerings such as *NetLogo*. Many of these agent-based simulations were spatial in nature, determining through complex interactions between multiple agents and decision rules where, for example, settlements might occur (with results compared against actual archaeological circumstances). The other approach was analytical, focusing on GIS-based methods or on new quantitative techniques. The latter include *spatial statistics*: sophisticated and computationally intensive methods developed largely by quantitative geographers that recognize interdependencies in spatially distributed information and how relationships change with spatial scale. Kernel density analysis, a form of neighborhood weighting, permitted generalization of spatial distributions that clarified patterns in graphical plots. Ripley's K (and related indices) enabled the formation of conclusions about clustering or dispersion of point patterns over a range of spatial scales. Global statistics, whether measures of spatial autocorrelation or based in multiple regression, were replaced with local indicators of spatial association and geographically weighted regressions, for example. Their adoption has been facilitated by open-source or free software such as *R* and *GeoDa*. Increasing quantitative sophistication is illustrated by superior methods for cluster detection that avoid the shortcomings of earlier approaches. Deficiencies in Ripley's K are even challenged by replacing its inherent Euclidean geometries with more realistic cost-of-travel distances to quantify inter-point relationships (see papers in Barcelo and Bogdanovic 2015).

GIS applications pertinent to spatial analysis have become more thoughtful and expanded into new domains (see *VISIBILITY MODELING*). In viewshed studies, the limitations of human vision have been considered through Higuchi and fuzzy viewsheds. With increased computational power,

the amount of land visible from *every* point in a landscape permits analyses of settlement location relative to view quantity. Viewsheds have also been applied to within individual structures to assess how they were intentionally constructed to restrict and channel vision and experience. Least-cost pathway analyses and the availability of large regional databases have addressed continental-scale migrations. Computationally expensive "from everywhere to everywhere" approaches now generate travel networks without pre-specified origin and destination points, giving a "neutral view" that indicates where travel was most possible in a region and which have been shown to coincide with known routes and settlements. At a within-site level, pathway analyses have expanded into urban settings or individual buildings. This work is often associated with "space syntax analysis" (see *ISOVIST ANALYSIS*), which assumes that spaces are shaped by social relationships that can be analyzed by reduction to a network of components represented as maps and graphs describing connectivity and integration.

Other recent computational methods include network analysis (see *NETWORK SCIENCE*), which detects patterns of relationships between subjects of interest in complex systems. Rooted in graph theory, it becomes a spatial method when subjects have geographical position represented by nodes (settlements, regions) and the links (trade, alliances) between them. Studies have shown relationships based not on spatial proximity, but according to social connectivity, where links cause certain archaeological occurrences that can be realized by mapping them.

Advances in spatial technology are changing how the data of spatial analysis are acquired (Comer and Harrower 2013). Global positioning systems (see *GPS (GLOBAL POSITIONING SYSTEM)*) routinely capture thousands of coordinates from field mapping projects. Multispectral classification of high-resolution air and space data can define settlements, mounds, and other archaeological features. Advanced pattern-matching algorithms identify regular geometric and anthropogenic shapes from air and space imagery, and mounds and depressions from light detection and ranging (lidar) data (see *AIRBORNE LASER SCANNING AND LIDAR*). These technologies also yield new kinds of information for analysis such as

mound or borrow pit volumes from lidar, or the definition of “anthropogenic areas” revealed by spectral characteristics or geophysical responses.

SEE ALSO: Cluster Analysis; Computer Applications in Archaeology; GPS (Global Positioning System); Multispectral and Hyperspectral Imaging; Remote Sensing; Statistics and GIS; Statistics in Archaeology

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Structure from Motion

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The term structure from motion (SfM) refers to the perception of three dimensions when the viewer is moving through space, as we do when we walk around a sculpture to understand its form. When a subject is captured using SfM the movement is usually represented by a series of digital photographs taken from different points. These are processed by computer software to create a point cloud representing the surfaces of the subject, which can be further refined to create a virtual 3D model.

SfM is a type of computer vision technology, using computers to visualize the world, which is driven by research in robotics and autonomous vehicles. The roots of SfM are in photogrammetry and stereophotogrammetry (see PHOTOGRAMMETRY AND STEREOGRAMMETRY), but the cameras used for SfM do not need to be calibrated. The process consists of several discrete steps which require an enormous number of calculations that are only made possible by modern advances in computing. The source photographs must be numerous enough to capture every surface of the target in three or more images and these must be recognizable from one image to the next. The features are analyzed by a scale invariant feature transform (SIFT) to find distinctive key points, which are matched across multiple photographs, then passed on to a process known as bundle adjustment. Bundle adjustment uses the focal length and the size of the camera's photographic sensor which can be derived from the meta-data tags stored in digital images, so it is important that the original photographs are used. Starting with a well-matched pair, lines of projection are calculated between the camera positions and key points. Each image is added incrementally and where it does not fall within the expected parameters it is rejected. As each image is added, the time taken to compare it

increases exponentially and most SfM software uses a system to break up the calculations into smaller parcels. The result is a collection of points representing the locations of the key points and the cameras from which the photographs were taken. If the matches are poor, more photographs can be added at this stage or the software can be asked to consider more key points.

The exact technique used next varies depending on the software. Some commonly referenced techniques are pairwise depth map computation, which uses triangulation to calculate the distance of a point from the camera, and patch-based multi-view stereo (see MULTI-VIEW STEREO) in which features are matched across several images and then expanded to include the surrounding pixels. The result is a dense point cloud representing the surfaces of the subject which can be converted into a 3D model.

In order for features to be matched they must be clearly visible in the photographs. A common reason for failure is grain or blurring caused by low light which can be overcome through the use of a tripod. Excessive digital compression artifacts can also lead to poor-quality results. If lighting is inconsistent across the photographs the features may not match correctly; the best conditions are bright but overcast natural light. Reflective or featureless surfaces are not suitable for SfM, but this is not usually a problem in archaeology.

The positions of cameras and points calculated by SfM have an arbitrary but uniform orientation and scale. In order to derive metric data from the point cloud it must be georeferenced using control points. Most SfM software will include a tool for adding control points and transforming the point cloud to the correct scale and geographical location. More control points will give a more accurate result, but the accuracy of the points in a point cloud is dependent on the accuracy of the control points. However, any errors are generally consistent across the scene, and the relative positions and precision of the points is good. A number of papers that have investigated the accuracy of SfM conclude that while not perfect it is sufficient for most purposes required by archaeologists (De Reu et al. 2013).

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The point cloud produced by SfM is similar to light detection and ranging (LiDAR) (see AIRBORNE LASER SCANNING AND LIDAR) and laser scanning (see LASER SCANNING), and consists simply of a list of points with color, position, and a value for surface normal, a vector which represents the surface direction. These can be used to produce a 3D model with a surface made of triangular polygons. The source photographs are projected onto the model to create a high-resolution texture that can be applied to the surface. Further processing allows a georeferenced orthographic image to be rendered from any direction, and an equivalent digital elevation map (DEM) to be created by writing the distance from the camera plane to the points on the surface.

“Bundler: Structure from Motion for Unordered Image Collections” was developed by Noah Snavely, based on the project “Photo Tourism: Exploring Image Collections in 3D” to exploit the large number of images that have been uploaded to the internet by the public. Snavely, Seitz, and Szeliski (2006) were looking at ways in which they could make sense of this huge amount of data. Their solution was to arrange the images in 3D space as if seen from their real-world camera positions. The ideas developed in “photo tourism” were adapted to create Microsoft’s Photosynth, which allows the creation of a low-density point cloud from source photographs. The earliest SfM software consisted of a number of scripts linking open-source versions of the core processes. One of these, open source photogrammetry, was released as part of the ArcheOS operating system and designed specifically for archaeologists. VisualSfM was the first fully functional SfM software to feature a user interface, and is free for noncommercial and academic use. Autodesk’s 123DCatch is another free software that uses cloud-based computing to process the photographs. The increasing awareness of SfM in archaeology, as well as its adoption for geographical survey and by the film and video game industry, has led to an increasing number of powerful commercial software solutions. The most notable of these is Agisoft’s Photoscan, a mid-range-priced software with a speed and ease of use that has made SfM a mainstream solution for a growing number of archaeologists. The entire SfM process including production of

models, georeferenced orthophotos, and DEMs can be performed inside Photoscan.

As an archaeological tool, SfM has potential for both recording and investigation. From its earliest employment by archaeologists it was identified as having the capacity to record information that would otherwise be lost during excavation (Doneus et al. 2011). As SfM software becomes more sophisticated its speed and accessibility makes it increasingly feasible to deploy it on site and capture a 3D model of the surface of each context before it is removed, without significant impediment to the process of excavation. The human interpretation of features cannot be replicated by computer vision, but SfM can be used as a complement to traditional plan and section drawing aided by total station (see TOTAL STATION) or differential global positioning system (DGPS). The models created by georeferenced point clouds are suitable for use in 3D geographic information systems (GIS) (see STATISTICS AND GIS), where they can be used, for example, to calculate volumes and visualize negative contexts. The creation of 3D models and georeferenced orthographic images while the excavation is in progress can help archaeologists in their interpretation of features and inform their ongoing course of action (Dell’Unto 2014).

SfM is a good way to capture the complex 3D shape of standing structures, making sense of the plan of a building that is not easily apparent from the ground. The model can be virtually split into cross-sections to examine the volume of the structures and can be used by conservationists to highlight weak points where problems may occur. Repeated models can be used to monitor changes in a building structure over time.

Aerial photography (see AERIAL PHOTOGRAPHY) has a long history of use in photogrammetry, and is an obvious candidate for SfM. The evolution of SfM has been mirrored by the development of low-cost camera-carrying drones (see DRONES), and archaeologists have also been able to achieve good results from light aircraft, cameras lifted by kite (KAP), and balloons (Verhoeven 2011). The resulting point clouds can be compared to the height maps created by LiDAR, with the added advantage that they contain color information. When combined with ground control points they can be used to

create georeferenced digital elevation maps and orthophotos which are precisely aligned. The density of information can reveal subtle features that are invisible to the observer at ground level, but it should be noted that unlike LiDAR, SfM is unable to penetrate vegetation, and therefore is less suited to areas with a lot of ground cover.

Surface information can also be acquired at the macro scale. SfM models can reveal slight deviations in the surface of objects, such as marks or engravings on stone. There are a number of treatments that can be applied to a 3D model to enhance surface detail. One of these is ambient occlusion which simulates light being shone evenly onto an object from all directions, as if from an overcast sky. Areas that are occluded such as small depressions in the surface receive less light and show up as darker areas (Spring and Peters 2014). Another is cavity mapping, which highlights concave surfaces. To further enhance surface detail, an SfM 3D model can be used to create virtual reflectance transformation imaging (RTI). Here a collection of orthophotos is created, each with a single light shining onto the surface from a grid of points. The RTI is then produced using these images instead of photographs.

Future developments of SfM are likely to address the long processing times and usability of the software. It is still prohibitively slow to create detailed point clouds of a large area which means that for archaeological sites and buildings the photographs must be processed and georeferenced in separate groups, then combined into a single scene. The development of mobile GIS (see MOBILE GEOGRAPHIC INFORMATION SYSTEMS (MGIS)) bringing digital recording into the field raises the potential of a more active role for SfM in facilitating the organization and planning of excavations. It should soon be possible to develop software allowing archaeologists to build up 3D models in real time as they take photographs. This would overcome the problem of poor photographic coverage that is only discovered when the subject can no longer be accessed. Immediate integration with 3D GIS would allow archaeologists to trace plans directly onto orthographic images of features, saving the time-consuming task of measuring every feature, and allowing them to concentrate on interpretation.

SEE ALSO: Computational Photography; Digital Photogrammetry; Image-Based 3D Modeling; Virtual Reality Modeling

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Structured Light Scanning

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Structured light illumination (SLI) is a category of techniques for extracting three-dimensional (3D) surface information from target objects, and is widely used in scientific, industrial, commercial, and entertainment applications at a variety of scales and resolutions. SLI involves the projection of a known pattern onto the surface of the target object and relies on optical triangulation to make depth measurements and 3D data acquisition possible. Visible light, infrared light, and laser light have been used in the projection of these patterns. A calibration process provides the baseline data that define any unknown triangulation parameters and allow for the depth to be known for each pixel in the camera. There are a variety of pattern types that can be used: single-dimensioned lines, two-dimensioned stripes, grids, or dot matrices (Chen, Brown, and Song 2000; see Figure 1).

SLI actively projects light into the scene, which is different from passive 3D techniques such as photogrammetry or from stereoscopic methods that use the available ambient light (see IMAGE-BASED 3D MODELING and STRUCTURE FROM MOTION). By projecting the pattern on the target, active 3D imaging techniques generate data from all parts of the target, whereas passive 3D techniques do not work well on flat or featureless targets. Because of this, active 3D imaging techniques like SLI will generally have greater accuracy, precision, and resolution than passive techniques.

SLI systems typically include a computer or other processing unit tethered to a camera and a projector. Recent innovations include scanning systems that are decoupled from the computer, allowing for smaller, lighter, and more robust scanners that can be taken into remote and hostile environments, including underwater (e.g., Crane et al. 2010; see Figure 2).

To use SLI, the projected pattern needs to be the main luminous source of a target object, in order to get proper contrast for pattern differentiation. In practice, this means that ambient light, typically sunlight, can pose a challenge to SLI scanning. Minimizing ambient light by darkening a room, by shielding or covering the target, or by scanning at night or during periods of low light may be necessary if one wants to generate high-quality data.

SLI has been used to generate 3D data at various scales, from small objects such as fingerprints or computer microprocessors to large targets such as progressive assembly facilities for manufacturing. The scale of the application has implications for the requirements of the projection system, as creating sufficient pattern contrast while projecting a large pattern will pose different challenges from projecting a pattern onto a very small target. In archaeology, most SLI has been focused on objects that are rather larger targets, for example excavation units or entire sites.

Commercially available SLI systems vary greatly in price and capability and can be divided into professional (or metrological) systems, which in 2017 ranged from around US \$10,000 to over US \$100,000. The resolution and accuracy of these units vary with the scale to which the technique is applied, but resolution of a square meter scan can be less than 20 micrometers, about the diameter of a thin human hair. Resolution can be much greater when the target area is smaller, down to one micrometer.

Consumer versions of SLI scanners are increasingly available, now on smartphones and very commonly as motion capture input devices for video games. These systems are much less expensive than the metrology-grade systems, typically in the hundreds rather than thousands of dollars for the professional scanners. Accuracy and resolution will be much lower than in the metrology-grade systems, and have typically run in the range of a centimeter, depending on the scale at which the system is being used. Most consumer-level SLI systems are used at room scale or as input for robotics, not for measuring



Figure 1 Structured light scanner in use.
Source: Author.

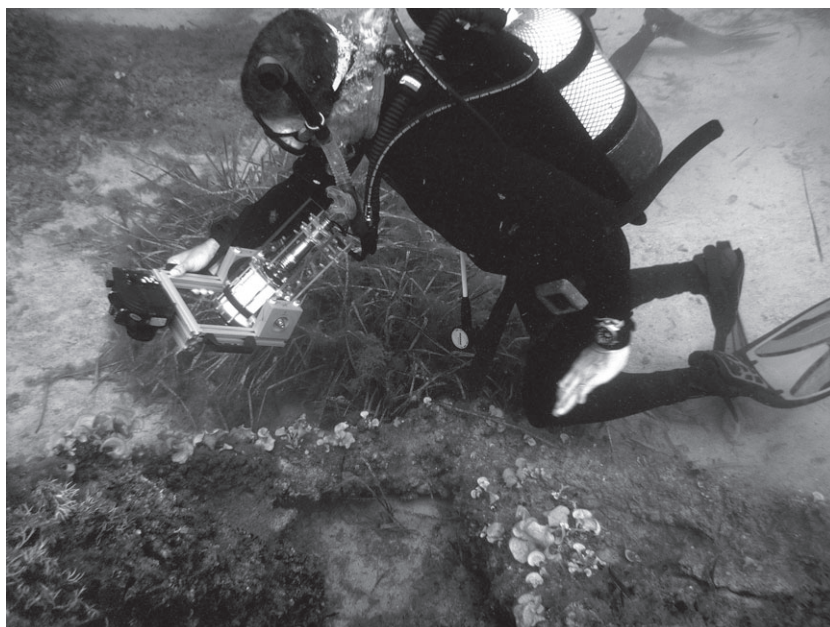


Figure 2 Prototype of an underwater structured light scanner.
Source: Author.

or recording the details of objects. The utility for archaeology would be at a similar scale, possibly for scanning a site, a large feature, or an excavation unit rather than for use at the object level.

In archaeological applications, SLI systems have been used primarily for object-level applications, for example applications in faunal analysis, lithic analysis, ceramic analysis, and the documentation of features such as petroglyphs (e.g., Manzano, Means, and Begley 2016; Crane et al. 2010). Passive techniques such as photogrammetry are currently preferred for site level applications, owing to ease of use, cost, and resolution needs. The intended use of the data is also a factor. The requirements in terms of accuracy and resolution will be different if the goal is to generate metric data from what they will be if the use of the 3D image is for presentation to the interested public on a website.

While SLI generates higher-resolution and more accurate 3D data than passive techniques in most cases, there are some significant challenges to archaeologists using SLI systems.

The metrology-grade systems are very expensive, and this may be prohibitive in many instances. Consumer-grade SLI systems are much less expensive, but may not offer the resolution or accuracy required, or may not offer significantly greater accuracy or resolution than passive 3D systems.

SLI systems are sensitive to ambient lighting. This may require special steps to ensure adequate pattern contrast for suitable 3D data. Inside a building, this is easily mitigated by darkening the room. Outside, or in environments where darkening the area is not an option, archaeologists may need to shield or cover the objects being scanned. When this is not possible, it may be necessary to perform the scans at night. This may raise safety concerns owing to limited visibility, or access at night may be problematic for other reasons.

While in most cases SLI scanning generates more accurate and higher-resolution data than passive techniques do, especially when the target is flat, smooth, or otherwise featureless, there are certain surfaces that pose a challenge for SLI systems as well. Transparent or reflective surfaces can be difficult to scan, as light may be reflected or otherwise affected in ways that interfere with

an accurate interpretation of the distortion of the pattern on the surface of the target object.

Finally, portability and durability may be an issue. While some rugged, lightweight, and easily portable systems exist (e.g., Crane et al. 2010), most professional-grade SLI systems are not suited for use in remote or hostile environments and are confined to laboratory or museum use, or to use on sites that are easily accessible.

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Three-Dimensional (3D) Facial Reconstruction

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Three-dimensional (3D) facial reconstruction or 3D facial approximation is a technique that approximates the face of an individual based on anthropological data regarding context and profile information, such as sex, age, ancestry, individualizing features, and pathologies. It may be applied in archaeological, museological, educational, and forensic contexts. In the field of archaeology, this technique has been used to generate visual interpretations of collected data, such as the facial reconstructions of King Tutankhamen, Queen Nefertiti, Simón Bolívar, St. Anthony of Padua, and St. Rose of Lima (Verzè 2009).

The technique consists of modeling the approximated face over a skull or its replica. Population-specific soft-tissue thickness data (from cadavers or living individuals) may be used as a reference to aid the reconstruction work. Markers placed on cranial landmarks assist the modeling phase, and some of the facial muscles and other structures may be reconstructed to enhance the individuality of the reconstructed face. For a thorough analysis and understanding of a cranium's main and specific features that may influence its facial appearance, an integration of specialists from different fields is desirable (e.g., forensic anthropology, forensic dentistry, head/neck surgery, pathology, forensic art) (Moraes, Dias, and Melani 2014).

The first publications in this field date back to the late nineteenth century. Examples of facial reconstructions from this period include the one of Johann Sebastian Bach, coordinated by Swiss anatomist Wilhelm His, in 1895 (Verzè 2009). Three main methods were developed during what might be termed the scientific

period of the technique's application. In 1920, Russian anthropologist Mikhail Mikhaylovich Gerasimov's method relied upon meticulous reconstruction of soft tissues from osteological anatomy. In the late 1960s, Americans Betty Pat Gatliff and Clyde Snow used a method that uses tissue depth markers as guides to sculpt the face. In the early 1970s, United Kingdom-based experts Richard Neave and John Prag integrated tissue depth data with anatomical reconstructions of the main structures that form the facial wireframe in order to perform approximations. These techniques became known as the Russian, American, and British methods, respectively, and were applied to a number of historical and forensic cases (Verzè 2009).

In referring to 3D reconstruction, it must be acknowledged that a variety of different materials and equipment may be applied to carry out this technique. Manual methods can be performed with modeling clay, while computer-aided techniques use digital tools, which may be semi- or fully automated. Technological advances and operational needs encouraged experts and investigators to develop the rebuilding process for digital systems using 3D computer graphics based around skull replicas obtained through computed tomography (CT) scans (see COMPUTED TOMOGRAPHY), laser 3D scans (see LASER SCANNING), and photogrammetry (see DIGITAL PHOTOGRAMMETRY). Conventional manual techniques carried out in virtual environments use software for modeling and animation, such as 3D Studio Max, Maya, and Blender 3D software (Figure 1). Open source software applications represent an alternative to commercial programs, which might help make these tools available to more investigators worldwide (Moraes et al. 2014). Recently, genetic analysis also has been used to estimate individual biological profiles and generate automated computer-aided 3D facial reconstructions. It is clear that this will form a key future research area (Claes et al. 2014).

SEE ALSO: Image-Based 3D Modeling;
Multi-View Stereo; Photorealism and Digital
Reconstruction; Structure from Motion;

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Figure 1 Lord of Sipán 3D facial reconstruction.

Three-Dimensional (3D) Printing and Additive Manufacturing

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Three-Dimensional (3D) Printing and Additive Manufacturing

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Three-dimensional (3D) printing, also known as additive manufacturing, is a collective term for a variety of closely related manufacturing and prototyping techniques involving the creation of a three-dimensional mesh file of an object's representation in the real world. This process was known as rapid prototyping, and around the world as automated fabrication, solid freeform fabrication, layer-based manufacturing, stereolithography, or direct digital manufacturing (Gibson, Rosen and Stucker 2014). Originally, additive manufacturing was developed with polymeric materials, waxes, and paper laminates, although a wide variety of materials can be used to create the model, such as plastic, metal, nylon, and glass. All modern additive manufacturing processes rely on the conversion of the mesh to a .stl (stereolithography) file, which describes the external closed surfaces of the original computer-aided design (CAD) model, and forms the basis for calculating the layers (Gibson et al. 2014). Once the file is input into the additive manufacturing machine and the parameters adjusted accordingly, the model can be built. Once completed, though, some cleaning (post-processing) may be required on some models before use: for example, removing support structures for overhangs. Some methods require more post-processing than others, such as cleaning off support structures, post-curing (exposing the model to a higher temperature to maximize some of the material's properties), and finishing, which can affect the final model's appearance and properties.

Additive manufacturing contrasts with machining a model, which subtracts materials from a block of raw material (Gibson et al.

2014). There are some processes where it is still preferable, for the sake of quality, to use machining techniques with certain materials over additive manufacturing. However, depending on the complexity of the model, additive manufacturing may be faster than other methods and is generally safer to use. Forging (also known as a formative process) is the other manufacturing alternative, where the material sets in molds. Forging is cheaper in some cases, but not as accurate. Additive manufacturing models also have many advantages over a drawing of an object (Gibson et al. 2014). Although the drawing is faster, easier, and cheaper to create, the model is in three dimensions and is much more representative of the final product.

Additive manufacturing methods can be broadly split into three groups: liquid, solid, and powder (Chua and Leong 2017). The main differences between these methods are the materials used, the creation time, and the accuracy of the models. Some methods involve a bed which moves as the model is created; others use a moving nozzle. The most accurate methods are rarely seen outside of high-end engineering industries such as aerospace and bioengineering. The most familiar method is known as filament printing. This normally involves a static bed of metal, with a moving head that is fed with a plastic filament that is normally polyvinyl alcohol (PVA), polylactic acid (PLA), or acrylonitrile butadiene styrene (ABS) prototype plastic. This method is relatively quick, although it is the least accurate method, having an error up to 5 mm. Therefore, this method is used in situations where accuracy is not a key consideration, such as for scale models for use in a classroom.

Liquid-based processes generally use a vat of photocurable resin, although other methods can jet drops of liquid photopolymer into a tray via a printhead (Chua and Leong 2017). The archetype of liquid-based processes is stereolithography, which builds up parts by using a vat of photocurable liquid that photopolymerizes when exposed to a laser, creating the shape one layer at a time. The method requires a support structure, and

although it is good for prototypes, it is prone to errors arising from the corrosive nature of the solvents used to remove the supporting structures and requires a significant amount of cleaning, post-curing, and finishing. Polyjet printing is similar to a conventional inkjet printer but uses an ultraviolet light source to dry the ink. This method can involve a great variety of materials but requires a water source. Multi-jet modeling, also known as CMJR, is similar to an inkjet printer but applies a thermopolymer material in three dimensions. The variety of materials one can use with multi-jet printing is limited. A lesser known technique is two-photon polymerization, which can build 3D structures without building up the model layer by layer. This involves firing a laser at photons which polymerize only when they simultaneously absorb the energy from the laser.

Physical methods use wires, filaments, rolls, or pellets delivered through a printhead, such as in filament printing, which is a simplified example of fused deposition modeling. This method heats thermoplastic material to a semi-liquid state and extrudes the material to the required area. It is a slow process, and has a restricted accuracy caused by unpredictable shrinkage as a result of the semi-liquid material re-freezing, but it can produce a large volume model with functional parts. Selective deposition lamination, or SDL, uses paper as its main material in small quantities. It applies adhesive droplets to the paper, using a laser cutter and knife to remove the excess material. This method creates relatively high resolution models for low cost because of the materials involved. It also creates low strength models with a small build volume. This is a preferred method for creating scale models of cities by planners and architects at a low cost. Physical vapor deposition printing uses stencil shadow masks to pattern thin films on a substrate. Sometimes this method involves releasing pulses of high electrical current applied to a skimming metal bed. It is considered the least efficient but most accurate method in manufacturing, with a tolerance of 0.005 mm; generally high purity metals such as copper, gold, nickel, and tin are used. Often this method is used for electronic devices, circuits, and systems, as this process keeps the properties of the metals. Laminated object manufacturing uses large sheets of metal, which are laser-cut into the required shape, and bound to

the next layer by a roller. It is low cost and is compatible with commercially-made sheet metal, although the size of the layers is much larger than other methods, and significant post-processing is often required (Bhushan and Caspers 2017). A lesser known physical method is electron beam additive manufacturing (EBAM), which uses a beam that melts metal onto the surface of the part. While this method can only be used with a very limited number of metals and overhangs are not possible in the model, it is low cost and easy to switch between metals.

Methods using powder-based materials melt the powder into the predetermined pattern in differing layers. Some plastics, such as mobile phone covers, are manufactured with a mold made of a powdered method because it is a good compromise of cost and materials, although the machinery is often cumbersome. A number of powder-based methods exist, some of which share characteristics with liquid printing, and others with physical printing, such as colorjet printing (Bandyopadhyay and Bose 2015). The oldest method in use is known as selective laser melting, which shares its origins with vacuum casting. The main difference between selective laser melting and selective laser sintering is that melting produces an almost 100 percent dense model, as opposed to just a shell, which means the final model is more accurate and stronger than sintering methods. Selective laser sintering is a high-quality but slow process, which is used for producing the tools used in forming and shaping sheet metal. Colorjet printing creates 3D prototypes by solidifying layers of deposited powder using a liquid binder. It can produce models in color, although colorjet printing produces less functional parts and has a poor surface finish in relation to other powder-based methods. Generally, these models are also weaker than selective laser sintering models. Sintered laser, or selection laser sintering, utilizes a high-powered laser to fuse small particles of material. During the process, the bed upon which the build is resting is repositioned, lowering by a single layer of thickness. This method is used for working with metals like titanium for creating very high-quality chess pieces, as well as welding metal to itself in a vacuum. The machinery is very expensive to purchase and complex to operate, and as such is rarely seen outside of the aerospace industry.

The most common application for 3D printing in archaeology is for scale replicas of sites and objects. As they require digital meshes, it is possible to use a 3D mesh from many digital methods, including photogrammetry, laser scanning (see AIRBORNE LASER SCANNING AND LIDAR and LASER SCANNING), and X-ray tomography (see X-RAY TOMOGRAPHY). These meshes are often created in a purpose-built software package (see IMAGE-BASED 3D MODELING). Furthermore, it is possible to reverse-engineer a CAD model (Gibson et al. 2014), such as using photogrammetry or a laser scan of a model to create a printed model of the original object. The reconstruction of cuneiform tablets, Roman tools, and the broken ceramic lion from Nuzi, Iraq, at Harvard University are examples of reverse-engineering an existing object by using photogrammetry to create the mesh of the model, then to extrapolate the broken parts into a single model, and printing the final model with a CNC-machined foam. This method of additive manufacturing is technically known as negative manufacturing, although the other processes involved can all be used in additive manufacturing. It is also possible to use additive manufacturing to create custom-built equipment for archaeological purposes, such as unmanned aerial vehicles. This equipment is often used for mounting more specialized equipment such as cameras purposes. The custom-made nature of these applications means that when commercially produced, these products can be significantly cheaper than their counterparts, or solve a long-standing problem, such as attempting to employ multimode and multichannel radar architectures within the same radar machine (Traill et al. 2014).

Other sectors that employ additive printing methods include the biomedical industry, where additive manufacturing can produce personalized prosthetics, organs, and skin replacement treatments. Printing of biological materials relies on specialized liquid printing methods that have to be used in sterile environments where a variety of cells can be randomly seeded on printed structures so that they can grow and multiply (Carlier et al. 2016). Oxygen must be able to access the mesh at all times; only biodegradable plastics can be used to hold the mesh together with hydrogels to encourage cell growth and multiplication (Kang et al. 2016). The tolerance for error in

bioprinting is in the micrometers, and uniquely there are risks in rejection and inflammation of cells, so scaffolding cannot be used in most cases as they may increase these medical risks.

Many educational establishments and schools have filament printing devices for outreach purposes and building concept models. It has been noted that additive manufacturing technologies have the potential to improve education by giving a sense of empowerment to the users (Shelley et al. 2015).

As the industry grows, it is expected that other sectors will look to employ additive manufacturing in new ways, potentially disrupting the way we approach archaeology with new solutions to long-term problems, and with increased collaboration with the engineering industry.

SEE ALSO: Airborne Laser Scanning and Lidar; Computer Applications in Archaeology; Image-Based 3D Modeling; Laser Scanning; X-Ray Tomography

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Viewshed Analysis

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Introduction

Modeling and computing visibility on terrains is a fundamental problem in terrain analysis and is at the core of numerous applications. With terrain data available from light detection and ranging (LiDAR) technology at 2-m resolution and below, modeling visibility on terrains has the potential to offer incredible accuracy. At the same time, handling large amounts of data poses challenges to the algorithms, which can run for days or longer before producing a result. Analyzing and optimizing the efficiency of algorithms is crucial when dealing with large amounts of high-resolution data. This entry surveys algorithms for the computation of viewsheds on terrains, with emphasis on the computational complexity. For a description of the applications of viewsheds in archaeology we refer to “Visibility Modeling” (see VISIBILITY MODELING) in this volume. We will start by introducing some terminology and definitions.

Terrain models

Modeling visibility on terrain assumes we are given a *digital terrain model*, or, in short, a terrain model. In practice, digital terrain data come as a discrete set P of 3D sample points, $P = \{p_1, p_2, \dots, p_n\}$, where each point is specified by its latitude, longitude, and the measured elevation of p_i , which we denote by $z[p_i]$. A terrain model consists of a set of sample points together with an *interpolation method* that describes how to obtain the elevation values for points other than the sampled points P .

The two most commonly used terrain models are the *grid* and the *TIN* (triangular irregular network). On a grid terrain the elevations are

sampled with a uniform grid. Grids can be used with a variety of interpolation methods, such as linear, bilinear, or nearest neighbor. A TIN terrain consists of an irregular sample of points, which are connected in a triangulation. The elevation of an arbitrary point on the terrain is interpolated from the triangle that contains its latitude and longitude. Put differently, a TIN models the surface as a mesh of triangles. Typically, the triangulation forms a Delaunay triangulation when projected on the horizontal plane. Both grids and TINs are used in practice, and a clear choice between them is not obvious as they both have pros and cons.

Visibility

Given a terrain model, two arbitrary points a and b are considered to be visible to each other if their *line-of-sight* ab (the line segment between a and b) lies entirely above the terrain (Figure 1a). The most studied visibility problem on terrains is the *viewshed*: Given a terrain and an arbitrary point v , the viewshed of v is the set of all points in the terrain that are visible from v (Figure 1b). In addition to viewsheds, a number of other visibility-related problems have been researched. The *cumulative viewshed* of a set of V of viewpoints is the part of the terrain that is visible to at least one viewpoint from V . The *visibility index* of a point v represents the size of the viewshed of v , where the size represents the number of grid points that are visible from v (on a grid), or the geometric size of the visibility map (on a TIN). On grid terrains one can further define the *total viewshed*: This is another grid, of the same size as the elevation grid, where the value at a grid point v represents the visibility index of v .

Efficiency and accuracy

In order to be useful in practice, algorithms that compute visibility need to be efficient (the time to compute the results is reasonable) and accurate (ideally, the computed results match the ground truth). It is obvious that the accuracy of the computed viewshed depends on the accuracy of

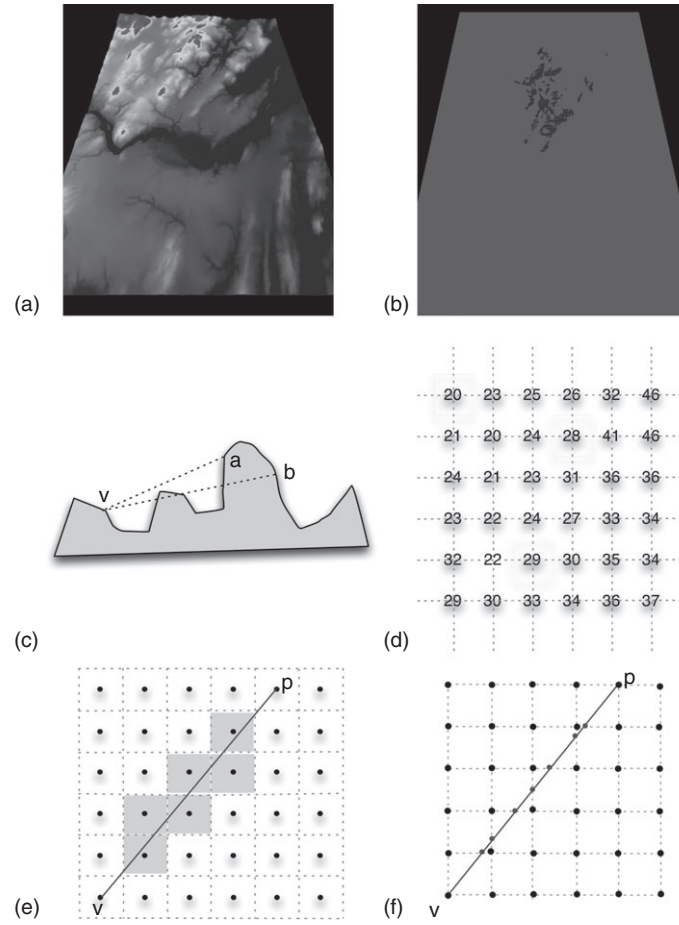


Figure 1 (a, b) Visualization of a grid digital elevation model (DEM) for Brunswick, ME, the United States. The viewshed of a point v at coordinates (100,100) from the upper left corner of the grid is shown in dark gray. (c) Two points on a terrain are visible to each other if the interior of their line-of-sight stays entirely above the terrain. Here (v,a) are visible but (v,b) are not. (d) A grid DEM and its associated matrix of elevation values. (e, f) To determine whether p is visible from v, the DEM needs to be interpolated along the line-of-sight vp. (e) In a stepped grid model, as used by Van Kreveld (1996), each grid point represents a square cell centered at that point. Cells that intersect vp are shown in gray. The elevation of these cells is considered to determine if p is visible. (f) In the grid-line model, the terrain is represented by connecting grid points with horizontal and vertical lines, and interpolating the elevation linearly inbetween points. Grid lines that intersect vp are shown in gray. The elevation of these points is considered to determine if p is visible.

the data: For example, a viewshed computed on a grid terrain at 1-km resolution is not going to be very realistic, no matter what the algorithm does. The second factor in the accuracy of the output is the algorithm itself: Given the same terrain model, various viewshed algorithms may obtain different viewsheds based on the models they use. An algorithm may introduce inaccuracy by

employing approximation to infer which points are visible without computing them explicitly, which overall makes the computation less accurate but more efficient. The interplay between accuracy and efficiency is important, and users that understand the models in which various visibility algorithms work are able to choose the right one for their particular application.

In recent years, with the advances of LiDAR technology, the accuracy of terrain data has gone up tremendously; terrain models at 2-m resolution are now common and consist of billions of points. Computing visibility on high-resolution data is very appealing in practice because of its accuracy; however, efficiency becomes the crucial issue. Many geographic information systems (GIS) offer modules to compute viewsheds and even total viewsheds. These algorithms tend to struggle when working on very large data and the computations can take many days or may not finish at all. This is one of the reasons that many researchers have worked on developing viewshed algorithms with improved efficiency. An algorithm's efficiency is characterized theoretically by the asymptotic complexity of its running time, which is described below. Theoretical running time analysis of algorithms aims to estimate how algorithms will behave in practice, and is crucial for understanding and comparing algorithms.

Algorithm running time analysis

The running time of an algorithm is modeled theoretically as the number of primitive “steps” executed in a generic computer where all instructions are assumed to take the same amount of time (the RAM model). In general, the time taken by an algorithm grows with the size of the input, so it is traditional to describe the running time as a function of the input size, n . The worst-case running time is the longest running time for any input of size n . When analyzing algorithms we are usually interested in the asymptotic efficiency of the worst-case running time, that is, how the running time increases with the size of the input, in the limit, as the size of the input increases. Asymptotic efficiency of the running time is usually expressed using $\Theta()$ notation. In short, a $\Theta()$ bound for the running time is a function that behaves asymptotically the same as the running time. For example, saying that the worst-case complexity of an algorithm is $\Theta(n)$ means that the worst-case running time grows as a linear function. We usually consider that one algorithm is more efficient than another if its worst-case running time has a lower asymptotic order of growth. This is not necessarily true in practice for small inputs (due to omitting constants and lower-order terms), but it is usually true for large n . Thus,

asymptotic analysis allows for a simple characterization of the algorithm's efficiency and also allows us to compare the relative performance of alternative algorithms; it is considered to be an excellent predictor of performance in practice.

Outline

The rest of this entry surveys known algorithmic results for computing viewsheds on the two terrain models that are being used in practice (TINs and grids), with emphasis on the computational complexity of their running time.

Viewsheds on TINs

Let T be a terrain represented by a TIN of n points. Recall that, given a point v , the viewshed of v is defined as the set of points of T that are visible from v . We refer to this as the *geometric* viewshed, to emphasize that it consists of all the points in the terrain that are visible from v and that we want the precise geometric shape of the viewshed. Put differently, for each triangle in the TIN, we want to find what part of it is visible from v . The viewshed of v is the union of all visible parts of all the triangles in the TIN.

An important issue to consider for a geometric viewshed is its size, that is, the number of vertices and edges on its boundary. The viewshed can intersect a triangle multiple times and a vertex of the viewshed is not necessarily a vertex in the TIN. It is known that in the worst case there may be $\Theta(n)$ triangles such that the boundary of the visible part of each of them consists of $\Theta(n)$ line segments, and thus a complete viewshed may have size $\Theta(n^2)$. A quadratic space complexity of the viewshed would make its computation unfeasible, especially on large TINs. Fortunately, in practice, the complexity of viewsheds seems to be close to linear. Some theoretical explanations are known. Most notably, it is known that the smoothed complexity of a viewshed is linear, based on certain assumptions on the shape of the terrain (De Berg, Haverkort, and Tsirgiannis 2010).

Several algorithms are known for computing geometric viewsheds on TINs. The algorithm with the best theoretical bounds on the running time is due to Katz, Overmars, and Sharir (1992) and runs in $O((n \alpha(n) + k) \lg n)$, where k is the size of

the viewshed and $\alpha()$ is the inverse Ackermann function. The algorithms introduce and exploit the concept of *horizon*: The horizon of a TIN terrain with respect to viewpoint v is a function $h(\theta)$ defined for any radial direction $\theta \in [0, 2\pi]$, such that $h(\theta)$ represents the minimum zenith angle which a ray from v with azimuth θ must have in order to be above the terrain. It has been shown that the horizon of a TIN of n points has complexity $H(n) = n\alpha(n)$.

Since the smoothed complexity of the viewshed is linear, algorithms that are sublinear in the worst case can be obtained only through approximation. One idea is to simplify the terrain to reduce its size and compute visibility on the smaller, simplified terrain. Another approach is to divide the area around the viewpoint into a number of slices, with each slice bounded by two rays from the viewpoint, and compute a one-dimensional viewshed along each ray; if the visibility map of the two rays bounding a slice is similar enough, the viewshed of the whole slice is constructed by interpolation between the bounding rays; otherwise the slice is subdivided into smaller ones. Both approaches were shown to give good results in practice.

In summary, computing geometric viewsheds on TINs has been thoroughly studied and several efficient algorithms are known. However, computing the exact geometric viewshed may not always be necessary (and some may argue that the shape of the viewshed inbetween the sample points is not accurate anyway). A “discrete” version of the viewshed may be defined as follows: the *vertices* of the TIN that are visible from v . That is, we are only interested in which sample points are visible and which ones are not. This is known to be a special instance of the *ray-shooting problem* which is the following: Given an arbitrary viewpoint v and a ray in the direction (θ, α) , find the first face of the terrain hit by the ray from v in the direction (θ, α) . The horizon tree by Cole and Sharir (1989) can be used to answer ray-shooting queries with respect to a fixed viewpoint in logarithmic time. It has size $O(n\alpha(n) \lg n)$ and can be built in the same bound. Given the horizon tree, determining which of the n vertices of the TIN are visible from v can be done in $O(n \lg n)$ time and $O(n \lg n)$ space.

Viewsheds on grids

Let T be a terrain represented by a grid of n points. Grids can be used with a variety of interpolation methods, such as linear, bilinear, or nearest-neighbor. Although viewsheds on grids could be defined in the same spirit as on TINs (exact geometry), the standard model on grids is a simplified, discrete one: The viewshed of v is the set of *all grid points* that are visible from v . As a consequence, the size of the viewshed is at most $O(n)$.

The standard approach for computing viewsheds on grids is the algorithm known as R3. The idea is the following: To determine whether a point p in the grid is visible from v , compute the intersections between the horizontal projection of the line-of-sight pv and the horizontal and vertical grid lines, and compute the elevation of the terrain at these intersection points by linear or bilinear interpolation (Figure 1c, d). If pv stays above all these points, then p is visible. R3 is considered to produce the “exact” viewshed (to the extent possible by the data); however, its running time of $O(n\sqrt{n})$ is too slow in practice. A different implementation of R3 that runs in $O(n \lg n)$ time is possible using the horizon tree; however, it uses superlinear space, which probably means it is mostly of theoretical interest.

A variety of algorithms have been proposed that are faster than R3 while approximating in some way the computed viewshed: Some algorithms consider only a subset of the $\Theta(n)$ lines-of-sight; others interpolate the line-of-sight only at a subset of the $O(\sqrt{n})$ intersection points with the grid lines; while others have some other way of determining in $O(1)$ time whether a point in the grid is visible. Examples are XDraw, R2, Backtrack, Van Kreveld’s radial sweep, and IO-centrifugal: R2 runs in overall $O(n)$ time, which makes it very appealing in practice. Several researchers report that it produces a good approximation of R3 that outweighs its loss in accuracy. Its main idea is to compute lines-of-sight only for the grid points on the boundary, and use nearest-neighbor to approximate the visibility of the interior grid points. The algorithm XDraw runs also in $O(n)$ time and is faster than R2, while being less accurate. A generalization of XDraw, described by Izraelevitz (2003), allows the user to

set a parameter k , which is the number of previous layers that are taken into account when computing the visibility of a grid point. The algorithm by Van Kreveld (1996) runs in $O(n \lg n)$ and computes the viewshed by rotating a ray around the viewpoint (Figure 1e, f). However, the viewsheds generated by this algorithm and R3 can be slightly different due to the different interpolations used.

Dealing with big data

A couple of approaches have been proposed for computing viewsheds on large, high-resolution terrains. The first approach is using the so-called I/O-efficient algorithms, that is, algorithms that optimize both the number of instructions and the data transfer between memory and disk. I/O-efficient algorithms are used in situations where the terrain is so large that it does not fit in the main memory of a computer and resides in virtual memory on disk. I/O-efficient versions of R3, Van Kreveld's radial sweep, R2, and XDraw are known; see, for example, TiledVS by Ferreira et al. (2012) and the algorithms by Fishman, Haverkort, and Toma (2009) and Haverkort, Toma, and Wei (2013). In practice, these algorithms scale up to terrains that are more than an order of magnitude larger than available memory, and can compute viewsheds on terrains as large as 28 GB in a couple of hours on machines with as little as 0.5 MB of memory.

Another approach for handling large data is high-performance computing and parallel algorithms. Recently, a number of authors have exploited the availability of multicore computers, super-computers, and graphics processing units (GPUs), and described parallel implementation of R3, R2, and Van Kreveld's algorithms. For example, Osterman, Benedicic, and Ritosa (2014) report an implementation of R2 that is faster than TiledVS, with a factor of 10 speedup using GPUs, when running on datasets up to 180 GB. Although these algorithms do not provide a theoretical analysis of their performance and it is not clear how results will carry over to other platforms, they are a promising first step.

Conclusion and challenges

A variety of algorithms have been proposed for the computation of viewsheds on both grid and TIN terrains. Computing the viewshed with the full accuracy allowed by the data is possible, but may be too slow in practice. Many algorithms exist that introduce approximation in the computation, but are faster. A careful assessment of the accuracy/quality of the viewsheds computed by the various algorithms remains to be carried out.

While there is a large body of work on computing viewsheds efficiently, very little is known about computing cumulative viewsheds and total viewsheds. For the total viewshed, the best algorithm seems to be the straightforward one: Compute the viewshed repeatedly. This will take at least quadratic time and is only feasible on very small grids. Developing improved bounds for these problems remains open.

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Virtual Reality Modeling

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VRM (virtual reality modeling) embraces all the real-time applications in archaeology dealing with virtual reality (VR), 3D modeling, data capturing and data archiving (i.e., 3D repositories, online archives). VRM redefines the digital workflow from fieldwork to the laboratory post-processing and real-time visualization. In fact, almost all the datasets produced during fieldwork activities are in digital format, and they actually migrate from one platform to another, but always in digital domains. In other words, most of them can easily be implemented for virtual reality applications.

Virtual reality involves modeling and simulation technologies for human interaction with three-dimensional visual content at different levels of immersivity and in a multisensory manner. The user interface can include gloves, goggles, wearable headsets, controllers, or other kinds of body interaction and simulation. The performance is typically in real time (at least 30–60 frames per second) and the modality of interaction is designed by software and graphic interface (GUI, graphical user interface). Although virtual reality technologies were invented in the 1960s, the most effective “reinvention” belongs to the game industry and the high graphic performances of personal computers. In the twenty-first century, virtual reality can be considered a revolutionary technology mostly because of the massive production of game technologies and inexpensive digital tools and devices and the introduction of personal immersive systems, such as Gear VR, augmented reality devices Oculus Rift, Google glasses, HoloLens, and the like.

The passage from fully immersive systems to massive virtual reality systems has completely revolutionized the use of VRM in archaeology, museums and digital archives. Online and open source platforms such as Sketchfab (a community of over half a million content providers) and

3D HOP (<http://vcg.isti.cnr.it/3dhop/>) show the relevance of Internet archives and repositories for the digital preservation, usability and dissemination of 3D models. The portability of models, from on-site data recording to immersive environments and/or online platforms, can possibly guarantee long-term digital preservation and adequate cultural transmission. They also improve the usability of models and the accuracy of interpretation for a large audience.

The definition of *model* is still debatable: virtual reality requires typically geometric meshed models, equipped with textures and color information. But in a broader sense, a model can be also a simulation, a mathematical unit or a process. VRM deals typically with geometric (meshed) models and point clouds, by on-site (empirical) data recording or by 3D graphic virtual reconstructions. The integration of empirical data collection and digital reconstruction/simulation deeply influences the interpretation and the creation of an inferential model.

A pioneering use of VRM in archaeology dates back to the 1990s, when Mark Pesce co-invented virtual reality modeling software (VRML, Virtual Reality Modeling Language) (Pesce 1995; Forte and Siliotti 1997), with the intent to display 3D (three-dimensional) models and scenes on the Web by real-time interaction. In the first book on virtual archaeology (Forte and Siliotti 1997), the chief editor (Forte) discussed the pioneering potential of VRML in relation to virtual archaeological reconstructions.

At the dawn of VRM, in the early 1990s, no personal computer was able to generate full real-time interaction (30–60 fps) with complex archaeological models or 3D scenes. This was the era of virtual archaeology (Barceló, Forte, and Sanders, 2000; Forte 2010; Forte and Campana 2017) where the models were generated by computer graphic rendering and not by real-time engines. The output related to rendered images and computer graphic animations, but with no interaction with models. In that context, the VRML had the utopian goal to transform Internet navigation into a 3D cyber-world. For archaeology, the initial

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pivotal goal was to transform static 3D models in interactive scenes, by merging empirical datasets with virtual reconstructions, via VRML. This preliminary software development did not succeed and the VRML did not become a standard. Such a lack of 3D standards is still an issue for online archives and 3D repositories.

In the last two decades, the amount of digital models and datasets in archaeology grew exponentially; this was due to the massive use of laser scanners, digital photogrammetry, photomodeling and remote sensing technologies (UAVs, lidar, micro-scale data recording). This proliferation of models and datasets was not guided by an adequate policy of data archiving or an open-access strategy.

The technologies of data capturing involve different categories of sensors, devices and tools: laser scanners, drones, lidar, and digital photogrammetry, for example. All the models are created by other digital datasets and not by analogue data. The new generation of VRM (real time, immersive, interactive) is associated with the revolutionary approach designed by cyberarchaeology.

The definition of cyberarchaeology was formally introduced and discussed for the first time in a workshop at the TAG (Theoretical Archaeology Group) Conference in Stanford (May 1–3, 2009) within the conference *Diversifying Participation: Digital Media and Learning*, and in a second workshop on Virtual Collaborative Environments for Cultural Heritage (February 18–20, 2010 in San Diego, La Jolla). The workshop organized for TAG was aimed at analyzing the epistemology of cyberarchaeology in relation to the research topics of the conference. The workshop in San Diego was mainly focused on collaborative virtual environments, virtual models and simulation studies. Finally, in a scientific monograph published in 2010 (Forte 2010), cyberarchaeology was accepted as a discipline with specific research perspectives. In short, cyberarchaeology is the science of multimodal 3D simulation/interaction of archaeological datasets in different domains. The massive use of 3D digital technologies in archaeology, in fact, is identifiable in new digital workflows and real-time simulation of archaeological datasets. Cyberarchaeology deals also with “big data”, like many other scientific fields of the digital era.

In fact, it is possible to estimate that around 2.5 quintillion bytes of data are generated every day; 80 percent of them were created in the last two years. Archaeology, on a very small scale, is part of this revolutionary social and technological change. The outcome of this revolution is a hyperdescriptive reality, where the impact of informational growth requires different inferential and epistemological models. The impact of this revolution has still to be studied in detail and with a new “digital metrics”.

This digital migration of data and models in such diverse domains creates unexpected results and more advanced knowledge. Study of the code is mandatory for re-analyzing the interpretation process in the light of a cybernetic perspective: the feedback created by different users operating in the same environment/ecosystem generates further feedback and unexpected interconnections. In the last few years, the implementation of 3D online platforms such as Sketchfab, Tdar and 3D Hop launched a new era of 3D browsing, where many users are also content providers or co-creators. In addition to the pure visualization, several tools are nowadays focused on simulation, annotation, and collaborative work.

From this point of view, the core of the process is not in the virtual model itself, but in the mutual relations produced by interaction/embodiment/enaction with the model. The study of VRM in cyberarchaeology is focused on these relations and on the capacity to generate new research questions during the simulation process. The interpretation of the model depends on the complexity of interaction and the level of embodiment of the user. Recent studies in neuroscience show clearly that the embodied simulation is a multimodal process (body–mind) able to discretize in affordances and spatial relations (Gibson 1979) our experience with/between objects and environment.

All perceivable information in the environment comes from a perceptual–motor interaction. The acquisition of data from the environment can be identified in the circularity between action and experience and between action and knowledge. This process can be seen at the intersection between empiricism and simulation: empiricism by developing tools for data capture and autoptic evaluation in the field; simulation in relation to data processing and modeling

in labs and virtual environments. Along with the functionality of VR to enable unique ways to integrate spatial maps and VR renderings through a series of virtual models, a second functionality deals with the ability to find relationality between many different digital media artifacts. Therefore, the archaeological interpretation is characterized by multivocality, collaborative work, networking, new digital media and open digital narratives; it is a fluid and open process.

VR interactions

Virtual reality systems are able to provide a three-dimensional embodiment and a high level of immersive engagement and interaction in relation to the software interface and models design. VRM requires different levels of immersivity and interaction, based on the modality of engagement between users, models, and virtual environments. For example, immersive 3D applications are aimed at simulating a sense of presence inside the application and, because of the spatial embodiment, to stimulate a more participatory involvement of the user. VRM applications can be classified in terms of level of immersion and interaction. For example, gestures, visualization, and multisensory involvement influence the user's feedback. Typically, these applications provide "walkthrough" or "flythrough" actions within the virtual environment, so that the user is involved as an avatar or in the first person. The role of the user is fully active and they are able to control the environmental conditions within the digital simulation as "human avatar".

One of the first experiments involving VRM in real time on personal computers was the reconstruction of the Paleolithic caves of Lascaux, made by Benjamin Britton in the 1990s, by Head Mounted Display (HMD) interaction (Forte and Siliotti 1997). Later, the project "Virtual Petra" hosted in the ArchCAVE at Brown University (Shape Lab; Joukowsky 2002) was one of the first immersive virtual reconstructions of a monument in relation to archaeological artifacts and strata.

Pivotal and early applications in virtual theaters were the NUME Project (CINECA, Bologna) and Rome Reborn (UCLA, Los Angeles, University of Virginia), both started in the late 1990s. NUME (New Electronic Museum of

the city of Bologna) was aimed at the historical reconstruction of Bologna, starting with the twelfth century CE. Rome Reborn (Kimberly et al. 2010) was focused on the virtual reconstruction of Rome around 320 CE.

In the twenty-first century, the use of immersive applications has involved museums, cultural and research institutions with the scope to involve a higher number of users in virtual environments, thanks also to a more extended use of personal computers. Major attention has been paid to applications involving a higher number of simultaneous users, and to increase the space of immersivity in archaeology. For example, the Virtual Flaminia Project (Forte et al. 2006) developed a collaborative application for multiple users with the scope to award navigation and interaction by digital teamwork and exploration. In the "Place Hampi" virtual museum (Kenderdine 2010), the interaction involves multiple users in a large virtual room.

Additional experiments with collaborative VRM involved teleimmersive technologies (Forte and Kurillo 2010). In 2010, a successful experiment with teleimmersion was accomplished by UC Merced and UC Berkeley: users from different university campuses were operating in the same cyberspace and sharing the same 3D data. The primary goal of such collaborative frameworks is to facilitate immersive real-time interaction among different 3D datasets and models. The main case study was the reconstruction of the excavation process of the Neolithic site of Catalhuyuk (Turkey). In this case, all the layers recorded by laser scanner, artifacts, GIS layers and databases were shared in the 3D space.

Micro-scale applications of VRM concern the virtual visualization and simulation of archaeological excavations, by layers, units, finds, and contexts. This is due mainly to the intensive use of digital photogrammetry (based on shape from motion and computer vision), 3D laser scanning, lidar, and remote sensing technologies (Forte and Campana 2017).

VRM in a time span of 25 years has revolutionized the approach to archaeological data, from fieldwork to digital simulation and VR reconstruction. The core question is always the representation of the past, its digital preservation, and its transmission to future generations. It is a broad research field since it involves the

use of digital technologies in the field as well as virtual reconstructions for real-time digital environments (HMD, augmented reality, desktop, immersive) or portable devices, such as smartphones, tablets, and the like.

The dissemination of apps for different devices, from immersive VR to smartphones and augmented reality, opens up new perspectives for VRM. For example, future digital publications in archaeology could be based on augmented or mixed reality tools and linked to public online repositories.

VRM datasets constitute the libraries of the future where the interpretation process is constructed during the virtual performance, and potentially every interaction can produce new knowledge and a different kind of learning.

SEE ALSO: Authenticity in VRM; Computer Applications in Archaeology; Image-Based 3D Modeling

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Visibility Modeling

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Visibility has always played a role in archaeological investigations. It can be found, explicitly or implicitly, in discussions on political power, territory and control, symbolism, social space, and so on. The possibility of modeling visibility has only been possible since the development of geographical information systems (GIS) and, to a lesser degree, other software platforms and paradigms such as space syntax and virtual reality. In the case of GIS, visibility modeling is achieved primarily through the repeated calculation, and combination, of *viewsheds*. A viewshed is best interpreted as a regular sample of the area of “potential visibility” around a point given on the topography (represented by a digital elevation model or DEM). Viewsheds refer to the visibility of a surface (mostly represented by a raster) and not to any target on it. By “potential visibility,” we refer to the surface area that remains unobstructed by topography. Locations (cells in a raster) that are visible from a viewpoint are usually encoded with a value of 1, those that are not visible with a value of 0. In this sense, viewsheds are better expressions of what remains hidden than what is visible. Early discussion of several of the limitations surrounding the use of viewsheds may be found in Wheatley and Gillings (2000).

Archaeologists have modeled visibility within a wide range of interpretative contexts, covering many archaeological periods and site types. Yet the nature of the questions has remained fairly narrow. For the most part, visibility has been approached as part of investigating the locational preferences of people in the past. Interest has been in assessing whether visibility was a factor when choosing the location of a particular site or monument. Many of the methods that archaeologists have used to study this topic rely on some Monte Carlo simulation variant where observed visibility patterns are compared against similar

patterns derived from random points (sometimes the samples are stratified, or controlled in some manner). The nature of the comparison varies: sometimes it will be based on whether existing sites have the same level of intervisibility as those generated randomly, whether local perturbations in site locations change significantly the size of visible areas associated with each site, or whether the content of the views are similar or not. Similarly, archaeologists have used certain methods to identify and describe the significance of certain natural features such as particular peaks or horizon shapes as seen from sites. Until recently, and despite the locational undertones, the majority of investigations have approached the study of visibility in isolation without considering how visibility may have interacted with other confounding factors. This is the subject of a paper by Eve and Crema (2014), who used point-based spatial statistical techniques to explore how the locational choices of several Bronze Age houses in the Leskernick Hill area (Cornwall, UK) may have resulted from the combination of visual and nonvisual factors as well as spatial interaction among pre-existing sites. To this day, however, the most common question that archaeologists continue to explore is whether sites are intervisible among themselves. This was first considered by Wheatley (1995) in his study of visibility patterns among monuments located on the Salisbury Plain and the Avebury region in the UK. This approach was further improved and extended by Fisher and colleagues (1997) when investigating the location of a set of Bronze Age cairns on the island of Mull (Scotland). Both studies relied on the calculation of *cumulative viewsheds*, raster layers generated by the repetitive “addition” of viewsheds where each location, or cell, contains the number of times that location is visible from one or more viewpoints. The popularity of this type of analysis has greatly benefited from the creation of specialized GIS toolkits such as those found in GRASS, and continues to be enhanced through the use of complex statistical methods as illustrated by Brughmans, Keay, and Earl (2014). In this work, the authors use a particular

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approach in network analysis, exponential random graphs models, to explore how the pattern of intervisibility among Iron Age and Roman settlements in southern Spain may have resulted from the repeated application of a set of smaller-scale (inter-)visibility goals.

In the course of their investigations, archaeologists have also sought to extend the standard output of the viewshed routine as a way to include other visual information or derive additional visual parameters. Thus, archaeologists have combined distance and directional information with the standard output of viewshed in order to further characterize viewsheds (how evenly distributed they are) and separate visible areas into distance bands (Wheatley and Gillings 2000). Similarly, the calculation of visual angles has allowed them to provide a (theoretical) measure of the level, or clarity, of cultural features or to distinguish visual planes, that is, foreground, middleground, and background (e.g., Llobera 2007). These studies are significant because they try to incorporate, within the limitations of the standard viewshed calculation, objects and/or a sense of scale. However, modeling visual parameters aimed at exploring more subtle qualities that refer to the appearance (what does it look like?) of the sites or monuments have been less forthcoming. Some early attempts may be found in the works of Lake and Woodman (2003). More recently, Llobera (2015) calculated angle of elevation and angle of incidence to investigate the appearance of Mamoas (round barrows) when viewed along the ridgeline on the Sierra de Barbanza (NW Spain).

It must be said that the majority of the studies mentioned above approach visibility by focusing on the relationship between points in isolation, and ultimately, resolving a simple question: whether a set of particular points (often standing for archaeological remains) are visible (not obstructed) from another set of points or from each other. Through the concept of visualscape, Llobera (2003) attempted to point out the limitations of this pointillistic view, and draw attention to the possibilities of retrieving structural properties of visual space. By this view, *cumulative* and *total viewsheds* (Wheatley 1995; Llobera 2003) are to be interpreted as particular expressions of such structures that might be studied in their own right. Similarly, the great majority of modeling

efforts have sought to produce static snapshots of the visibility patterns for specific time periods. So far, limited work has gone towards understanding the process by which these visual patterns emerged and the significance of such a process for landscapes (see Llobera 2007; Brughmans et al. 2014, for some hints and early explorations).

Finally, it is important to acknowledge some of the more subtle implications that surround current GIS-based visibility models. A viewshed is the result of repeatedly connecting two points with a line (of sight, or LoS) and checking whether this is interrupted by the intervening topography. Using LoS as a way to explore (potential) visibility has both advantages and disadvantages. The viewshed routine, currently, allows us to generate quite easily the different views from and towards a point (sometimes referred to as *projective* and *reflective* viewsheds), which may be used to model paths with different visual qualities. With some notable exceptions, within the current viewshed paradigm, modeling efforts are somewhat constrained to representing features as combinations of points which might, without careful consideration, have unintended consequences. Despite criticisms (see above), visibility modeling represents a vibrant area of research which is likely to grow in future years.

SEE ALSO: Isovist Analysis; Viewshed Analysis; Virtual Reality Modeling

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Visualization of Ground-Penetrating Radar Data

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Ground-penetrating radar (GPR) is an active electromagnetic technique which delineates changes in the dielectric, conductivity, and overall electromagnetic properties of subsurface materials. GPR systems emit electromagnetic pulses of a central frequency into the subsurface. The electromagnetic signal is reflected or refracted upon converging with variations in the subsurface material, the amplitudes of which are presented almost immediately during survey. Three-dimensional (3D) renderings can be “sliced” to specific depths that are estimated by calculating the relative velocity of the subsurface material and two-way travel time to be exported as raster images or 3D animations. Recent work has further explored the integration of GPR data, other geophysical data, and remote sensing data with digital terrain models and light detection and ranging (LiDAR) data.

History of visualizing GPR data

The first application of what could be considered a crude GPR system was used to measure the thickness of ice on glaciers in 1929 Austria. The use of GPR expanded to use in geology and utility surveys in the 1970s, by which time the United States National Aeronautics and Space Administration (NASA) had built a GPR system to send to the moon. From the mid-1970s to the 1990s, the use of GPR systems, and geophysical survey in general, in archaeological science grew immensely. The 1980s saw a major growth in the use of GPR systems for landscape surveys, particularly in Japan (Conyers 2013). However,

at this time, processing reflection profiles was problematic as they were printed on paper. In 1982, the first datasets were corrected for relative soil velocities. Moving into the 1990s, major improvements to GPR survey and data processing came with technological advances, particularly in computer hardware and ad hoc processing software. It became much easier to process data as they were stored on digital files during survey. After 1993, the field also saw the first use of amplitude slice maps, computer-simulated two-dimensional (2D) models, and 3D reconstructions with these computing improvements (Conyers 2013).

In its initial stages, commercial GPR data were collected along coarsely spaced traverses in analog and digitized as 8-bit, whereby interpretation and, when possible, processing were quite time consuming (Conyers 2012, 48). Reflection profiles were printed on paper and from these profiles responses were hand-drawn as crude contour maps of anomalies (Conyers 2012, 49). Today, digital data are collected and presented almost immediately in the field as 16- or 32-bit data, and 0.5 ha of gridded data can be rendered for interpretation in less than 30 minutes.

Image processing and rendering

Once the radargrams have been processed to reduce noise and create spatially accurate data, they can be presented as radargrams, slice maps, 3D animations, and isosurface models, and overlain with other forms of geophysical and remote sensing data. In 3D rendering, the space between radargrams is interpolated; as such, the first step to producing high-quality raster outputs is to collect high-resolution data in the field (Leckebusch 2003). The primary methods of interpolating between data are kriging and inverse distance. Kriging solves an inverse covariance matrix to abate the error between data and interpolated points, often producing superior results (Goodman and Piro 2013).

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Inverse distance interpolation is faster and more mathematically simplistic, where nearby points are averaged to estimate an interpolated point, based on the distance to the interpolated point. Weighting is proportional to the inverse square of the distance between a known point and the estimated point (Goodman and Piro 2013). Once grids are interpolated there are two options: If data were collected in zig-zag or global positioning system (GPS)-tracked mode, grids will need destaggering; if data were collected over multiple days or vastly different geologies, grids may require mosaic correction to reduce the effects of variable moisture content, weather conditions, equipment settings, and/or geological contrasts across a site (Conyers 2013).

Post-processing data

As with other geophysical techniques, prior to rendering, datasets must be processed. Radargrams and depth profiles are comprised of pulses transmitted by the GPR antenna and the response from the ground surface, subsurface material, and GPR signal noise. In order to analyze only the responses from the subsurface material, extraneous data can be processed and rectified. Though some GPR systems record and present minimally processed gained data in the field, filtering is necessary to view later-arriving reflections, determine and correct for relative soil velocity, and remove noise. The processed signals are then compiled to be rendered as raster images, vector data, and animations. The frequency, amplitude, velocity, and phasing of reflection waves are particularly important to processing and interpreting GPR data (see Table 1). Importantly, however, it is vital not to overprocess data or arbitrarily apply filters to datasets as this could produce distorted, uninterpretable data.

Radargrams or *depth profiles* are 2D representations of an individual traverse (Figure 1a). As such, these files are quite easy to view in basic software with little processing. Nevertheless, corrections for gain, migration, and direct current (DC) drift are still necessary. Profiles are particularly useful for viewing hyperbolic reflections during the interpretation stage of a survey, but alone are not a viable method to

visualize entire sites as they are not a complete “picture” of the subsurface nature of an area, rather just an individual traverse. Therefore, when interpreting results it is recommended that profiles be viewed in conjunction with slice maps, as XY trace plots are viewed alongside grayscale plots when interpreting other geophysical data.

Slice maps or *amplitude maps* are sections of gridded data at a specified depth below the ground surface, called time slices (Figure 1b), that demonstrate the scale and spatial distribution of responses (defined herein as a change in amplitude) in a given area. Rendering data this way allows for a plane view of any responses of interest and provides the end user with 3D data. Maps can be presented as a single slice or a series of stacked slices that demonstrate the change in an anomaly as depth increases (Conyers 2016, 13, 119). Slice maps are the most common method of visualizing GPR data as they provide a complete view of a given area. The slice thickness and overlap are set by the user, which allows for targeting specific depths. Once time slices have been created, they can be interpolated and transformed into an animation. Animations allow the end user to visualize the changes in the subsurface matrix in real-time, which aids in identifying subtle changes and patterns.

Modeling and simulation has developed since the 1990s when Dean Goodman created software to simulate archaeological features in GPR datasets based on known or expected electromagnetic and morphological properties of buried objects (Conyers 2016). By inputting parameters such as dielectric permittivity, conductivity, and morphology into the software, 2D reflection profiles are created from artificial simulated wave paths (Conyers 2016, 41). Simulated models are useful in demonstrating how a buried object may present differently within a range of geological background materials (Conyers 2012, 50). 3D models can also be used to show the volumes and morphology of anomalies of interest. It is important to note that the accuracy of simulated models is entirely dependent on the quality of the known values used to create the model.

Isosurface rendering generates 3D surfaces which represent points in 3D space measuring a

Table 1 Common usage and effects of GPR signal processes (Goodman and Piro 2013)

<i>Process</i>	<i>Purpose</i>	<i>Effect</i>
Resampling	Correct variation in the number of scans per user-set navigation marker and create accurate spatial density information	Sets the number of scans per user-set distance unit to a constant by interpolating between scans to create additional scans
Gain	Visualize later-arriving, weakly visible attenuated reflections	Intensity, or amplitude, of radar reflections increases
Migration	Correct for signal spread and subsurface velocity distortion, particularly over variable terrain which causes signal diffraction, skews two-way travel time, and distorts morphology of responses Estimate relative soil velocity based on the principle that broad hyperbolic reflections indicate fast velocity and narrow hyperbolic reflections indicate slow velocity	Removes extraneous hyperbolae by determining the “point source” of reflections by averaging the reflection energy of each hyperbola in the dataset. In Kirchhoff migration the angle of incidence and depth of reflective feature undergo a correction based on a tacit velocity profile, reducing positional errors and collapsing hyperbolae
Hilbert transform	Visualize weak reflections by considering absolute value of data and connecting peak responses	Fourier transform (FT) is run on radar pulses, negative frequencies are shifted 90°, and then an inverse FT is run, creating a signal in the positive domain and represents the envelope of recorded pulse
Background removal	Filter out horizontal banding caused by signal noise in order to view slight reflections near the surface	Algorithms determine average waveform across a radargram and subtract this value from all in the dataset
Bandpass filter	Remove noise resulting from post-processing gain and “ringing” or signal noise from antenna	Utilizes one-dimensional Fast Fourier Transforms (FFTs) to remove noise from radargrams. FFTs convert radar pulses/signals into their spectral components (amplitude and phase at each detected frequency). Radar waves can be low-pass filtered or high-pass filtered
Spectral whitening	Remove noise resulting from post-processing gain and “ringing” or signal noise from antenna	Normalizes real and imaginary spectral amplitudes by converting data utilizing FFTs and setting the magnitude of spectral frequencies to 1
Deconvolution	Minimize negative effects of previous processes	Spectral division deconvolution utilizes FFTs to convert data to the frequency domain, remove the antenna’s impulse frequency by dividing the frequency response of the radargram by the frequency response of the impulse, and revert data back to the time domain Cepstrum deconvolution normalizes the data using a logarithmic scale. Predictive deconvolution utilizes the preceding signal to predict the succeeding value in the radar scan

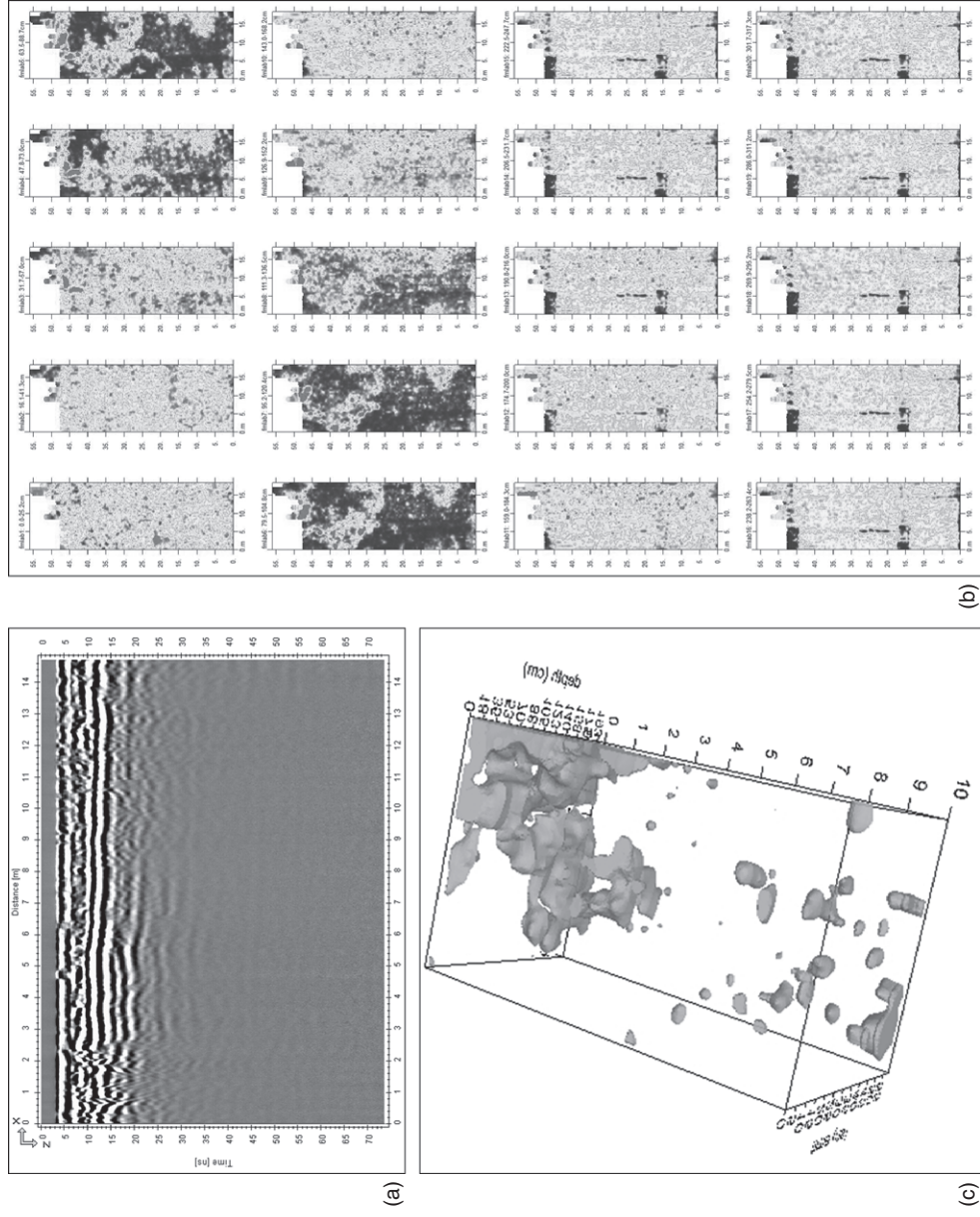


Figure 1 Selection of rendering options. (a) Depth profile; (b) time slices; (c) isosurface.

constant value, which in the case of GPR is often the amplitude of reflected waves (Figure 1c). Visualizing data in this orientation is particularly useful for extracting responses of interest. As isosurfaces can be rotated and coded to show all aspects of an anomaly, they are a key tool in representing and understanding the full extent of buried objects. Isosurfaces can be imported into computer-aided design (CAD) programs to be georeferenced and combined with geographical information system (GIS) data and other forms of geophysical data.

Data fusion and *multicomponent integration* allow the end user to merge data from a range of geophysical techniques, remote sensing, and spatial datasets. As most geophysical techniques measure one property, combining data to create a multicomponent 3D dataset can improve accuracy and confidence in interpretations. This is key when visualizing and interpreting GPR data which often contain a large number of anomalous responses. Integrating datasets highlights responses of archaeological potential hidden among extraneous responses. Kvamme (2007) discusses the merits of various integration approaches, such as mathematical and statistical operatives (e.g., Boolean union, Boolean intersection, thresholded binary sum, principal components analysis, k-means cluster analysis, binary logistic regression), computer graphics solutions (e.g., 2D overlays, red, green, blue (RGB) color composites), and vectorized interpretative integration.

Interpreting GPR data from an archaeological perspective

GPR data can be presented in RGB value color scales or grayscale to aid in the interpretation of data (Figure 2a,b). Choosing a color scale is particularly important in presenting GPR data, in part because of the wide range of responses and slight variations in measured amplitude often encountered in datasets (Conyers 2012). Applying a color scale based on the standard deviation from the mean is far more accurate than assigning the color scale based on the range of values in the dataset (Goodman and Piro 2013). Plotting in color helps to visualize weaker responses as there

are more color assignments available. Also, they produce contrasts in the dataset which might not exist in reality as a result of color strength, thus the need for grayscale plots. Grayscale data are plotted with equal weighting on all reflections, but often cause weaker reflections to become obscured in datasets with a large range (Goodman and Piro 2013).

The color scales in a given plot coarsely correspond to numerical values indicating the amplitude of a response. Sliced data can be plotted in relative normalization or absolute (Figure 2c,d). In relative normalization, colors are assigned relative to the strongest response in that given slice. This shows weakly visible responses but will plot the same response differently in multiple time slices. Plotting in absolute is similar to clipping magnetic or resistivity data. Responses are colorized with respect to the maximum and minimum values of the dataset, which produces a more consistent scale but tends to remove weakly visible responses. Best practice is always to view the data in both aspects to be able to accurately interpret the origin of any anomalous responses.

Interpreting GPR data is often considered more complex than other techniques (Conyers 2012; Goodman and Piro 2013), partially due to the nuances of processing the data but also because of the sheer number of objects GPR could possibly detect. It is important in interpretation to not only look for “anomalies” but to view the entire “picture,” as areas of no or low reflection can be as telling as stark high-amplitude responses. While many advances in GPR data collection and processing have been made since the 1990s, further enquiry is necessary to fully grasp its applications to archaeological investigations. Particularly, the effects of traverse and sampling interval size on data quality and the ease and confidence of data interpretation requires exhaustive analysis. With growing popularity in remote sensing, automatic feature detection and extraction can also be useful in GPR surveys provided a comprehensive characterization of archaeological materials is conducted. However, these methods with respect to archaeo-geophysical datasets are still in their infancy as training systems and datasets are still being compiled for machine learning methods.

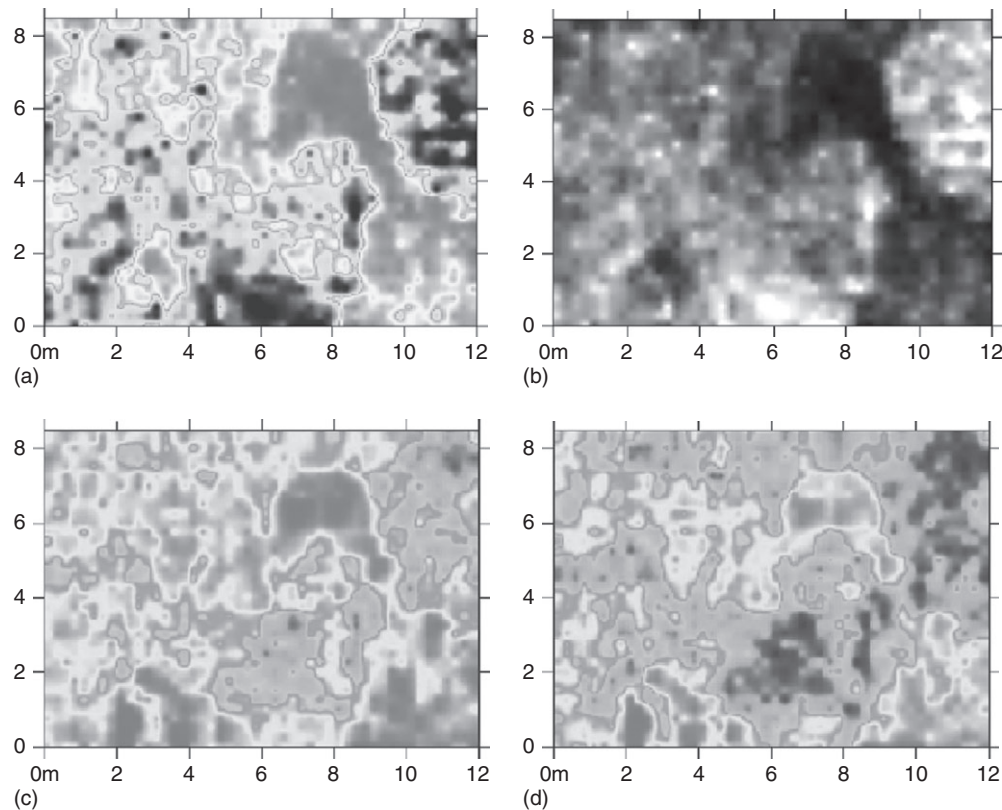


Figure 2 Examples of data presentation formats. (a) light grayscale; (b) grayscale; (c) absolute plot; (d) relative normalization.

SEE ALSO: Archaeological Sciences;
Ground-Penetrating Radar; Visualization of
Magnetometer Data

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Visualization of Magnetometer Data

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Magnetic survey is one of the most efficient and useful geophysical survey techniques. Due to the rapid data acquisition that is possible, large areas of land can be covered relatively quickly, at a high spatial sampling resolution. Due to the speed and detection success rate, magnetic survey is currently the most relied-upon archaeological geophysics surveying technique, and is consistently seen as the workhorse of archaeological geophysics.

Effective and efficient computer processing of magnetometer data is essential as landscape cover, survey speed and efficiency, and therefore raw data, increase every year. Appropriate data processing and visualization is as important as the collection of data in the field, as it transforms raw data into information which can be effectively interpreted. The aim of the processing and subsequent visualization is thus to provide both the specialist and the non-specialist with a dataset that can inform decision-making and risk management in a sensible and accurate way.

Data collected in the field can, in its raw state, contain various sources of interference, noise and errors, which can detract from the dataset and obscure anomalies of archaeological interest from identification. In the broadest of terms, such sources of noise can be classified as “spikes, stripes and zigzag effects” (Ciminale and Loddo 2001, 239). The treatment and processing of magnetic data is therefore designed to remove such faults within the data, while enhancing anomalies of particular interest. Data processing is usually conducted on specialist or customized software programs, of which a variety exist with broadly similar overall statistical and algorithmic functionality.

Magnetometers (see MAGNETOMETRY) are passive instruments and will record any detectable

ambient magnetic field. The Earth’s magnetic field is extremely strong compared with anomalies of archaeological interest, and to compound the issue, the Earth’s magnetic field also fluctuates diurnally. Therefore data collected within the field will sometimes need to be pre-processed before further visualization techniques can be applied. In the case of magnetometers set up in variometer or single sensor configurations, for example, the diurnal variation of magnetic field strength will need to be accounted for. For other magnetometers where a fixed configuration is always set to a gradiometer, the Earth’s (as well as local) ambient magnetic field is usually removed from the readings at the survey setup, known colloquially as a zero or balancing point. In this instance, no further pre-processing is usually necessary.

Key processing routines

Data are downloaded from the instrument onto customized software packages via a cable, or more recently, passed from instrument to computer via a data-stick or wirelessly. The data streamed out of the instrument are usually in the format of a series of values (in nano-Tesla, nT) that can be viewed within a simple text editor. The format of the data contained within downloaded files will depend upon both the instrument and software used. When data are first entered into a processing package, the individual data-files may need to be mosaicked so that they are positioned in the correct order for the entire survey to display correctly (if surveyed in a gridded mode). If the data have been collected incorporating satellite positioning, then the raw data will be automatically positioned, with real-world coordinates attributed to each data value. The necessary data processing for magnetic data can vary from site to site, and various methods of enhancing or suppressing the data in specific ways will depend upon the site itself as well as the rationale and aims of the survey. The processing algorithms within the software are objective, mathematical, raster-processing functions, but the way they are used and manipulated for data visualization

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is a subjective task for which the geophysicist is responsible. The following outlines a generic, basic processing procedure which would remove the most common sources of noise, and help to enhance anomalies of archaeological interest.

Magnetic data are usually “clipped” to diminish the influence of large, strongly enhanced (and reduced) anomalies within the dataset that may not be of any archaeological significance (such as field boundary fences or utility pipes). Usually a statistical model of the data is used to influence the clipping limits of the data, which may be set to a number of standard deviations of the dataset’s mean, or can be set to specific threshold values. Data with a low standard deviation but a large data range may require clipping, for example, as the majority of the archaeologically important data are almost always within one or two standard deviations of the dataset’s mean. Removing or suppressing large outliers within the data will also mean that they have less influence over more subtle statistical algorithms within the later processing stream.

Further visual improvements of magnetic data may include the suppression of both “drift” of the magnetometer and any heading errors introduced into the survey by the surveyor or sensors. These errors can be seen within the data as striping along the direction of traverse within the shade plot, as the background level of the data increases and reduces for each direction change. The background level for magnetometer data should be at 0 nT (when the Earth’s magnetic field is removed) and, as every magnetic anomaly will have an equal positive and negative field, the mean value of the entire dataset, and hence each traverse, should also be 0 nT. By using a process sometimes dubbed “zero mean traverse” or “de-stripe,” the background level over a whole traverse is adjusted down to the desired value of 0 nT. This greatly improves the quality of the data, and eliminates striping from the dataset.

Spikes are extreme readings or outliers within the dataset that may be caused by instrumental malfunction, or more likely by the presence within the soil of ferrous objects or high susceptibility debris, usually, but not exclusively, modern in origin. A de-spike function within most processing software will remove these strongly enhanced/reduced dipole anomalies

in the data caused by such point sources, and replace the offending data point with the median or mean of the data surrounding it. De-spiking of the dataset will therefore help to eradicate the distracting dipole point anomalies and improve the overall visualization of the data. Not all anomalies that look like spikes are necessarily non-archaeological in nature, so caution needs to be applied when using such functions.

Surveys walked without satellite positioning, and thus by a reliance on consistent walking speed, can suffer from a defect known as “stagger”. This is especially common for surveys walked in a zig-zag mode, usually by inexperienced or tiring surveyors, or when a significant topographical slope within the survey area affects the walking speed in one or both directions. If the walking speed has altered significantly between traverses, the resultant data will look extremely muddled, and be difficult to interpret. Such errors in data can make linear features appear disjointed or “like a zipper” in appearance (Aspinall, Gaffney, and Schmidt 2008, 124). A de-stagger function can shift traverses individually by a certain number of data points so that such archaeological anomalies line up correctly. It is important to make sure that staggering in the field is kept to a minimum, as shifting a traverse one way by a single data point will delete a data point from the end of the traverse, and create a false data point at the beginning. Excessive de-staggering of data can result in large areas of false data being created at grid edges, which both hinders interpretation and makes the dataset look amateurish.

Further visual improvements can be made to a magnetic dataset to increase the general appearance, and smooth out certain aspects of the data. Filters, such as a low-pass or median filter, are sometimes used to iron out small-scale, high frequency anomalies that may still exist. These generally work as a moving window algorithm over the dataset. Such windows will calculate an ideal reference value for the center of the window and replace the current center value if it is beyond a certain threshold. The data can also be interpolated, which is a process of falsely increasing the spatial resolution of the data so that blocky features become more rounded and natural. Both of these functions, if used well, can enhance the visualization of the data dramatically,

but the geophysicist must be careful to not lose subtle anomalies of archaeological importance by over-smoothing the dataset.

Visualization of processed data

The visualization of processed magnetic data has evolved at pace over the last half-century, as computing power and software capability has increased. Before computers could be used to visualize and digitize magnetometer data, manually drawn trace plots were utilized. This process, however, became ultimately “tedious and expensive,” and was eventually supplanted by digitizers (Clark 1996, 133). Another method of visualization, known as dot density plots due to the procedure of shading different data values, was first used by Scollar and Kruckeberg (1966) and became an effective computer visualization tool. With further advances in software, and on-screen and printing resolution, shade plots became the preferred method, providing an easy-to-interpret, map-like overview of the dataset, in which anomalies of archaeological interest could be identified through their form, magnitude, and size. Usually, magnetic data in a shade plot are presented in a linear grayscale, although conventions on color scales vary, and color can be used to highlight particular statistically enhanced or reduced magnetic anomalies of interest. Computerized trace plots are sometimes still used in geophysical reports and publication, and allow the viewer to assess the nature of the data in more detail. A further advance to some survey systems, accentuating the need for fast data processing, has been the development of processing algorithms that remove errors automatically (Eder-Hinterleitner, Neubauer, and Melichar 1996). Such has been the development over the last 20 years that real-time automated processing of magnetometer data over a 4G/wireless link is now a reality.

Once data are processed, they are usually georeferenced into a geographical information system (GIS), computer-aided design (CAD), or graphics package for further interpretation and inclusion in a survey report. Data are usually presented in a two-dimensional, georeferenced raster grayscale shade plot, and an archaeological interpretation is conducted using vector graphics in a layered system, allowing the geophysicist

to turn on or off the particular interpretation classes to highlight different aspects of the data. The visual range of the data is usually limited to a few nT either side of zero for final publication. However, this is dependent on the magnitude of the archaeological anomalies to be highlighted. In the UK, for example, ± 2 nT up to ± 10 nT may be fairly common display ranges for relatively “average” sites, where a reasonably strong magnetic contrast exists. In cases where the overburden to archaeology is large, or the magnetic contrast is particularly weak, this scale can be made even tighter, for example down to ± 1 nT, to try to accentuate the weak magnetic anomalies as much as possible. The choice of the display range is subjective, but should highlight the anomalies of archaeological interest, as well as all other anomalies of importance, as this can dramatically alter the ability to interpret and translate the data in an informed and complete way.

Other visualization techniques are sometimes incorporated to help aid interpretation, such as draping data over a digital elevation model (DEM), or lidar data to help to position subsurface anomalies within a real-world landscape. Magnetometer data may also not necessarily always be considered on their own, and complementary geophysical techniques will aid interpretation of the datasets. In the case of multiple surveys conducted over the same area, visualization techniques can be considered that combine the magnetic data with other geophysical techniques (Schmidt 2001; Kvamme 2006a). Such visualizations involve statistical manipulation of the data, and the use of color accentuates the various anomalies present in each dataset. Further visualization of the magnetic data may involve three-dimensional surface creation or modeling, although the latter is still generally rare in a common geophysical project.

SEE ALSO: Gradiometry; Magnetometry; Visualization of Ground-Penetrating Radar Data; Visualization of Soil Resistance Data

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FURTHER READINGS

Visualization of Soil Resistance Data

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Background and history

Resistivity survey instruments measure the ability of the ground to resist an electric current. In the past their analog output was visualized by plotting directly onto an x-y plotter, or readings were taken from a meter dial while hand-recording these values on paper. From these values, resistance profiles could be graphed (see Clark 1996 for examples of early resistance data visualizations), or, for a grid of readings, they could be manually contoured or used to create “dot-density” plans. In dot-density plots, each sampling unit—normally a 1 m grid—was manually “dotted” with randomly placed dots, the number of dots being proportional to the value of resistance. While field recording remained manual, mainframe and minicomputers, when available, were employed to automate contouring and dot-density visualizations of the resistance data. In the 1980s, analog meters were replaced by digital displays. Following this, digital data recording was introduced, in which an analog to digital converter allowed data to be stored, downloaded, and manipulated by computers. Digital data processing and the availability of high-resolution grayscale and color graphics have impacted on the visualization of resistivity data. Area resistance survey is variously termed *earth* or *soil resistance/resistivity*, or *geoelectrical* survey, while depth profile surveys are termed *pseudosections*, *geoelectrical* or *electrical imaging*, or *electrical* or *resistivity tomography*.

Area survey correction, processing, and visualization

Most commonly soil or earth resistance survey (ER) readings are taken on a regular grid, often at 1×1 m reading intervals for general prospecting, and are surveyed in survey grid units such as of 20×20 m, which gives 400 readings in each survey grid. Multiple survey grids are then combined to make the overall survey dataset *composite*. However, data collected with the twin electrode array, the most frequently employed array, have an inherent data-correction requirement, because the resistance reading is affected by the remote electrode positioning, requiring grids to be matched. This is accomplished by adding to one grid or subtracting from it a bias value, so as to make it match the adjacent grid; and this is done manually or by computer algorithm. Without correction, the survey grids would show and would visually and mathematically interfere with any analysis. Twin electrode data may need destriping and, where the immediate surface is very dry or stony, a despiking algorithm may be needed to remove extreme or spurious readings caused by poor electrical contact. Survey electrode arrays such as the Wenner or square arrays do not require grid matching or destriping. If surveys are conducted over an extended period of time, then there may be grid-matching issues that are not due to the array but result from overall changes in ground moisture conditions, which affect the range and contrast in the values. While range-matching algorithms help correct such differences, large surveys should be completed rapidly, by using multiple or mechanized instruments, or should be surveyed under the same ground moisture conditions.

After data correction there should be a clean set of resistance values that can be visualized. While early work used contouring and dot-density plots for visualizing the data (e.g., Clark 1996, figs. 2 and 110 respectively), grayscale plots are now

almost universally employed. In grayscale plots, white is more frequently used for low resistance and black for high resistance. Some reverse this scale, as human vision is more sensitive to changes at the light end of the grayscale than at the darker end of the range (Dennis 2004). In practice, the grayscale should be always reversed during analysis, to avoid this issue.

Visualizing the raw data as a grayscale plot with the range from the minimum (white) to the maximum (black) values and with linear intervals for the shades in between may produce the desired archaeological outcomes. In practice, it is likely that the data range will need to be clipped—that is, the minimum plotting value increased and the maximum decreased—often by being set at plus or minus a number of standard deviations, to bring out more visually low-resistance and high-resistance anomalies by increasing their contrast. The use of standard deviations is rather problematic, as resistance survey data do not normally produce a Gaussian distribution of values. If they do, then it is likely that the site is devoid of any archaeological or other anomalies of interest, and you are just measuring natural random variation in an otherwise uniform geology. That the distribution of resistance values is not normal is down to the physics and to the way the resistance is measured.

The difference between *resistance* and *resistivity* is that *resistivity* is the *specific resistance* of a material. Small Perspex resistivity “soil boxes” can be used to make measurements of resistivity. As the resistance recorded by the survey instrument is a measure of resistivity, and as it is changes that need to be mapped, converting all our resistance values to resistivity is not required. However, the resistance measured is a bulk value. For any resistivity array, a calculation of resistivity can be made; but, because of the unknown inhomogeneous nature of the subsurface, this can only be a “sum” of all the relevant contributing elements, and so it is termed an *apparent resistivity*. It is only required to calculate apparent resistivity when there is a need to compare or combine results from different arrays, or when creating depth profiles.

For a feature in ground of the same size, shape, and depth that is, equally, less resistive or more resistive than the background value, the more resistive feature will cause a greater

absolute resistance value change than the lower resistive feature. This means that earth resistance surveys show high resistivity features such as walls much more strongly in relation to background values than low resistivity features such as ditches, the latter being also inherently likely to be of lower resistivity contrast anyway. This further means that the resistance data distribution from a typical archaeological site is skewed, with the tail toward high resistance. This can result in poor visualizations, if simply an equal number of plus or minus standard deviations is used. To alleviate these issues, three approaches can be taken:

1. Manually selecting the clipping values by inspecting the histogram of the data. This allows visual emphasis on values that are beyond the clipping values and provides a more subtle view of variations within the mid-range of values, which are likely to be features within the background variation that can only be identified by pattern and morphology.
2. Using histogram equalization to spread out and allocate equal numbers of data points to each grayscale class, which in effect flattens the histogram. As in (a), this, without clipping, groups extreme values together, while further spreading the mid-range values to allow the detection of subtle anomalies that may exist within the noisy part of the distribution.
3. A nonlinear (e.g., logarithmic) scale which compresses the high resistance tail and has more class intervals at the low-resistance end of the distribution, so that subtle low-resistance contrast anomalies are brought out at the expense of the high-resistance part of the distribution. Such nonlinear scaling is frequently used in electrical imaging (see below).

Ideally, earth resistance data should be visualized without further processing. In practice, earth resistance data can benefit from applying mathematical filters either to enhance individual readings by removing wider background values (high-pass filtering) or to suppress individual readings so as to remove “noise” in the data and see larger features more clearly (low-pass

filtering). The latter can be used where the immediate surface has an extremely variable resistance, causing deeper, weaker anomalies to be drowned out by this “noise.” This is because resistance arrays are most sensitive at the surface, the sensitivity falling off rapidly with depth (Clark 1996, fig. 25). Such visually intrusive noise is caused by recent cultivation, extreme stoniness, or in dry conditions and a low-pass filter can remove it, but this will be at the expense of smaller anomalies of the dimensions of the reading interval.

While resistance arrays detect down to an infinite depth, most of the response will come from near the surface, where the archaeology is; but strong underlying geology may drown out subtler archaeological variations. A high-pass filter uses a “window” of values, for example 3×3 or 5×5 , to emphasize the central value and to remove the background.

Filtering needs to be done with a clear understanding of what is being lost and gained. In reports, it is a requirement that the unfiltered data be presented along with the processed data, to allow the user to visualize any gains and losses. Additionally, filtering alters the original values of resistance measured and, in the case of high-pass filtering, introduces negative resistances unless a bias is added, making numerical scales meaningless. The effect of applying both low-pass and high-pass filtering sequentially to the same dataset is illustrated in David, Linford, and Linford (2008, fig. 24), although it is debatable whether the final twofold filtered grayscale image enhances an interpretation provided by the raw data visualization. Other filtering methods can be applied to remove or reduce the visual effect of cultivation lines that may appear on surveys (Dennis 2004).

An alternative to the presentation of resistance data as a plan is to create a three-dimensional surface where the resistance value is used to create what is effectively resistance topography. This presentation is particularly useful for earth resistance data, as high-resistance peaks often relate to “positive” archaeological features such as walls, while low-resistance troughs often relate to “negative” archaeological features such as pits and ditches. These plots can be more visually appealing and understandable to nonexperts, but seasonal reversals of negative features and paradoxical responses may diverge from such models.

Electrical imaging

Where resistance data are collected at differing electrode separations along the same traverse, the resistivity can be calculated and plotted at notional depths below ground level. The value of the notional depth is related to the particular array and the electrode separation. For a twin electrode array, the factor is 0.867 the mobile electrode separation (see Loke 2016, table 2). Using these values it is possible to visualize the data as a sectional elevation through the subsurface. The raw resistivity data values can be presented as what is termed a *pseudosection*, or a mathematical inversion used to estimate the true values of resistivity in the subsurface, both as shown in David, Linford, and Linford (2008, fig. 25). Note that the visualization scale is in color and is nonlinear, and the depth scale is exaggerated. This is the most frequent mode of visualization for electrical imaging data, although grayscale visualizations are also used.

A number of such depth profiles are combined to create a three-dimensional block of data, then cutaway models or generating isosurfaces can be used to visualize the data within the block. The latter isolate volumes or data that are above, below, or between set threshold levels. This visualization of individual anomalies allows the user to investigate morphology and physical relationships. Three-dimensional visualizations are common across a range of archaeological data and for more general information the further reading sources should be consulted.

Data fusion and resistance data

The most challenging approach to visualizing earth resistance data is to combine these data with other geophysical or related datasets. Complex methods have been explored by researchers such as Watters (2006), but the most obvious one is to combine resistance data with topographical data by draping the former over the latter in a three-dimensional visualization. This is useful on sites with slight earthworks representing potential walls and ditches, which would correspond to high- and low-resistance anomalies; the two datasets visualized together

can enhance the interpretation of each, taken individually. In addition, extreme changes in topography can introduce false anomalies that could be interpreted as archaeological features and not simply as topographical effects in the data. Attempts have been made to combine resistance and magnetometry data, either mathematically or by draping the magnetic data over a wireframe representation of the resistance data. A visual approach is using color palettes (e.g., white–red for soil resistance and white–green for magnetometry) that, when overlaid and when the colors are mixed, allow the user to see where anomalies are only high-resistance (red), only positively magnetic (green), both (brown), and low or negative (white). Attempts to combine the earth resistance data with other datasets visually or mathematically are problematic because of the issue of assigning the relative weighting of different datasets to the final visualization.

SEE ALSO: Electrical Resistivity; Electromagnetic Conductivity; Visualization of Ground-Penetrating Radar Data; Visualization of Magnetometer Data

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